MANUFACTURING FLEXIBILITY IN THE JUSTIFICATION OF ADVANCED AUTOMATION INVESTMENTS

A THESIS

SUBMITTED TO THE DEPARTMENT OF INDUSTRIAL ENGINEERING

AND THE INSTITUTE OF ENGINEERING AND SCIENCES

OF BILKENT UNIVERSITY

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

MASTER OF SCIENCE

By

Sıla Çetinkaya

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I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Prof. Charles H. Falkner(Principal Advisor)

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ABSTRACT

MANUFACTURING FLEXIBILITY IN THE JUSTIFICATION OF ADVANCED AUTOMATION INVESTMENTS

Sıla Çetinkaya
M.S. in Industrial Engineering
Supervisor: Prof. Charles H. Falkner
August, 1991

A substantial amount of literature pertaining to flexibility has accumulated over the last decade. Nevertheless, there are several strategically important issues underlying this concept which are not understood properly. Understanding flexibility is made difficult by its multidimensional nature. Based on a detailed review of the literature we classify the conceptual frameworks on formalizing flexibility as:

- type based understanding
- change based understanding.

We suggest the change based approach can provide a greater understanding of flexibility to managers whose knowledge about technological details is limited. Thus we expand Suresh's (1990.b) **capability-ease** definition to provide a basis for the understanding.

There have been a prevailing discussion between researchers on how flexibility relates to system performance. In fact type based and change based approaches are two different ways of determining relevant performance measures associated with flexibility. We suggest a framework **capability-ease approach** for the analysis of relevant performance measures. If it is followed by a task force capability-ease approach can contribute to a greater understanding of flexibility which leads to the selection of more appropriate performance measures.

It is well recognized that for the future of manufacturing, flexibility is a crucial concept. However flexibility investments have been difficult to justify because of their high initial costs and strategic implications. Over the last few years incremental implementation of flexible technology has been suggested as a remedy for the investment justification problems, because it leads to lower annual capital outlays. We develop a **mixed-zero-one, nonlinear programming, multimachine, multiperiod, replacement** model for incremental implementation of flexible automation. Capability and ease notions are adapted for modeling flexibility and a reclassification of costs is considered. Thus some specific aspects of designing flexibility are modeled in contrast to machine-level equipment replacement problem.

Keywords: Manufacturing Flexibility, Justification of Advanced Automation, Flexible Manufacturing, Replacement Analysis, Investment Analysis.

ÖZET

OTOMASYON YATIRIMLARININ DEĞERLENDİRİLMESİNDE ÜRETİM ESNEKLİĞİ

Sıla Çetinkaya
Endüstri Mühendisliği Bölümü Yüksek Lisans
Tez Yöneticisi: Prof. Charles H. Falkner
Ağustos, 1991

Son on yıl içerisinde ' üretimde esneklik ' konusunda pek çok bilimsel çalışma yapılmıştır. Ne var ki, üretim esnekliğine ilişkin ve stratejik açıdan önemli temel kavramlar tam olarak anlaşılamamıştır. Üretim esnekliği çokboyutlu bir kavramdır. Bu nedenle de anlaşılması güçtür. Bu çalışmada, geniş kapsamlı bir literatür taraması sonucu, üretimde esnekliğin anlaşılmasına ilişkin yaklaşımlar iki ana başlık altında toplanmıştır:

- esneklik türlerini esas alan yaklaşım,
- değişimleri esas alan yaklaşım.

Değişimleri esas alan yaklaşım, teknolojik detaylar konusunda bilgileri sınırlı olan üst düzey yöneticilere, üretim esnekliğinin anlaşılmasında kolaylık sağlar. Bu nedenle çalışmamız kapsamında, ' değişimleri esas alan yaklaşıma ' göre esnekliğin iki bileşeni: **yeterlik ve kolaylık** kavramları tanımlanmıştır.

Üretim esnekliği ve sistem performansı arasında ne tür bir bağlantı olduğu halen bir araştırma konusudur. Aslında enekliğin anlaşılmasına ilişkin yukarıda belirtilen iki yaklaşım, esneklik ile bağlantılı performans ölçütlerinin belirlenmesinde kullanılabilir. Çalışmamızda esneklik ile bağlantılı performans ölçütlerinin analizinde kullanılmak üzere bir yöntem :**yeterlik-kolaylık yaklaşımı** önerilmiştir. Bir task-force tarafından uygulandığı taktirde yeterlik-kolaylık yaklaşımı üretim esnekliği kavramının daha iyi anlaşılmasına ve bu kavramla ilişkili uygun performans ölçütlerinin belirlenmesine katkıda bulunabilir.

Piyasa koşullarının belirsizliği karşısında, üretim sektörünün geleceği açısından esnekliğin önemi bilinmektedir. Ne var ki, yüksek ilk yatırım maliyetleri ve stratejik etkileri nedeniyle esneklik yatırımlarının ekonomik olurluğunu kanıtlamak güçtür. Bu güçlük gözönüne alınarak, esneklik yatırımlarının ' aşamalı uygulaması ' (incremental implementation) önerilebilir. Çünkü aşamalı uygulama daha düşük yıllık nakit çıktıları gerektirir. Çalışmamızda, esneklik yatırımlarının aşamalı uygulaması amacına yönelik olarak, yatırım ve üretim planlama problemleri gözönüne alınarak **karışık-sıfır-bir değişkenli, doğrusal olmayan, çok makinalı, çok dönemli** bir model geliştirilmiştir. Bu modelde üretim maliyetlerinin sınıflandırılmasında yeni bir yaklaşım kullanılmıştır. Esneklik özelliğinin modellenmesi amacıyla yeterlik ve kolaylık kavramlarından yararlanılmıştır. Böylece, esnekliğin belli başlı ekonomik getirileri makina yenileme problemi bağlamında gözönüne alınmıştır.

Anahtar sözcükler: Üretimde Esneklik, Otomasyon Yatırımlarının Ekonomik Analizi, Yenileme Analizi, Yatırım Planlama.

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Chapter 1

Introduction

The 1980's were characterized by the volatility in markets and the drastic improvements in production technologies. Therefore, firms in the highly industrialized countries have begun to adopt strategies for increased manufacturing flexibility in order to cope with shrinking product life cycles, ever increasing customer demand for a wider diversity of products, shortened delivery times, differentiation of markets into specialized niches and fierceing worldwide competition. Besides, as global competition grows, new manufacturing technologies should be applied to adopt to a rapidly changing manufacturing environment. Faster responses are needed to changes in market demand and manufacturing processes, and thus flexibility has become a key consideration in design of manufacturing plants.

Historically flexibility was introduced as an essential planned property of flexible manufacturing systems (FMS.s). Because flexibility in manufacturing without sacrificing efficiency became possible after the design of FMS.s. Now, computer integrated manufacturing (CIM) is believed to be an important factor in achieving flexibility. Thus, a microprocessor technology underlies flexibility. However, careful planning of manufacturing activities, an atmosphere encouraging innovative design, and an approach to continuous product improvement are also presumed to be necessary in achieving flexibility. In fact, the implementation of flexibility goes beyond the shop floor and permeates the business systems of the firm. Therefore, the concept manufacturing flexibility should not be restricted to FMS.s. The generalization; *almost all production systems are flexible,* *but to a certain degree*, is the origin of the idea that flexibility can be achieved in any system more or less. Throughout this study our discussion on understanding and measuring flexibility is not restricted to FMS.s. In general we use FMS.s as examples and mention flexibility investments or flexible technology referring to flexible manufacturing cells (FMC.s), flexible transfer lines (FTL.s), computer integrated manufacturing (CIM) systems as well as FMS.s.

A substantial amount of literature pertaining to flexibility has accumulated over the last decade. On the other hand, although flexibility has been a recurring theme in recent years, the idea is certainly not new. A historic perspective of flexibility from economic, organizational and manufacturing views is provided by Sethi & Sethi (1990). In this study we concentrate on the concept of manufacturing flexibility. Numerous definitions of manufacturing flexibility exist in the literature, but in general it is conceptually defined as *ability of a system to cope with changes effectively.* Thus, manufacturing flexibility is widely accepted to be a hedge against uncertainty of the manufacturing environment.

It is well recognized that for the future of manufacturing, flexibility is a crucial concept. Nevertheless, there are several strategically important issues underlying this concept which are not understood properly. First of all, there is still not a consensus on a precise definition of flexibility which captures all aspects of the concept. Many authors try to explain flexibility by classing it into types. More than fifty different terms for various types of flexibilities exist in the literature causing a confusion. Kumar (1986) states that, because different researchers emphasize different types of flexibility, the concept, manufacturing flexibility, is poorly understood. The lack of consensus on how to define flexibility by capturing its all aspects is due to the multidimensional and complex nature of the concept. It is clear that there is a need to standardize the meaning of flexibility, and do a taxonomy of flexibility which will remain as an area of future research.

Flexibility is emerging as a competitive weapon in today's manufacturing environment, and thus it is accepted to be an important dimension of manufacturing strategy. If flexibility is well understood, it is more likely to be incorporated in manufacturing strategy.

Nevertheless, despite the fact that flexibility is extremely important, it is not a *panacea* for the ills of manufacturing industries. However, understanding flexibility is vital for innovative design, proper economic justification, careful planning, better implementation, and critical performance evaluation in order to have realistic expectations from flexible technology. In Chapter 2 of this study, we review the literature on definitions and characteristics of flexibility under the title *Understanding Flexibility*. Our aim is to emphasize the importance of understanding flexibility and discuss the relationships between various lines of research on definitions and content of flexibility concept. In general we classify the literature on definitions and analysis of flexibility into:

- type based understanding of flexibility, and
- change based understanding of flexibility.

While articles citing expected benefits from flexible technology are abundant some companies' experiences have shown that the actual performance of this technology may not achieve expectations. Actually these failure stories can be viewed as the symptom of the basic misunderstanding that flexibility is a *panacea*. For an optimal design, understanding flexibility is critical in order to determine the extent of automation, especially in a labor intensive environment such as Türkiye or when some other alternative technology exists. Even though understanding flexibility is necessary for predesign, it is not sufficient for success. Because flexibility is a design invariant under uncertainty, there is a need to measure flexibility in order to guide design specifications.

On the other hand, poor actual performance of flexible technology is often due to implementation management. The lack of insight on flexibility and the inexperience of firms in managing flexible systems are usually among the primary reasons for this problem. Even if an appropriate design is selected, a performance deterioration may be caused by management due to the lack of a feedback mechanism on performance. Monitoring the effectiveness of the system after installation is a basic requirement for successful implementation. Success stories on flexibility investments can not completely be credited to the mere introduction of hardware and software. Because adopting flexible technology is associated with a learning curve, continual improvement on this curve can only be achieved by close evaluation of system performance. Since flexibility is a critical component of manufacturing performance, there is a need to measure and evaluate flexibility of the system. Flexibility measurement can facilitate whether or not the expected level of flexibility and its benefits are achieved, and also can provide a valuable tool used by operations managers to reach promised performance levels. This explains why measuring flexibility is crucial for operations managers who are interested in achieving continual improvement and providing all advantages of flexibility during implementation. Thus we can say that if flexibility is widely understood and if its measurement can be ascertained in a way that is meaningful to the managers, then flexible technology can be implemented more successfully.

In summary there is a need to measure flexibility in order to:

- guide design specifications,
- evaluate investment alternatives, and
- set performance goals and achieve continual improvement.

Measuring flexibility is an area of current research and there have been a number of attempts to suggest measures of flexibility. Based on a detailed review of the literature we find that these measures tend to be nonfinancial, local and isolated; focusing primarily on physical characteristics of the system. They ignore the importance of factors like operating policies and managers' attitudes and preferences. In their survey article Sethi & Sethi (1990) reveal that very little work has been done to develop analytical models that deal with measurement of flexibility rigorously. Buzacott (1982) states that while quantitative approaches to measure flexibility need to be investigated further, thinking about flexibility in a formal way provides useful and helpful insights. That is, all the underlying aspects of flexibility, including its multidimensional and complex nature, should be well understood before investigating quantitative approaches for measurement. This explains why we treat the problems of understanding and measuring flexibility in an integrated manner in this study.

Chapter 3 provides a review and a critical discussion of the literature on *Measuring Flexibility*. In order to better understand flexibility a framework for the analysis is suggested at the end of Chapter 2. We call this framework the *capability-ease approach* for understanding and measuring flexibility. The capability-ease approach explains how flexibility relates to system performance and also gives a crude idea on how to measure flexibility. In general, flexibility measurement can be done in two ways:

- Measuring flexibility as a value *(total system flexibility)*
- Measuring the effect of flexibility on system performance

Note that, it is meaningful to measure manufacturing performance by monetary terms when justifying flexibility investments. A proper justification process for flexibility investments can be viewed as measuring the effect of flexibility on system performance, and system performance is the monetary returns of the investment project over a specified planning horizon. Thus the problem of justifying flexibility is dependent on the problems of understanding and measuring flexibility.

Due to the increasing recognition of the strategic importance of flexibility, there will be widespread adoption of flexible technology all over the world. In many instances the use of flexible technology can easily be validated conceptually. At the same time, it is well recognized that flexibility investments can easily fail economic justification. Articles citing the inadequacy of traditional engineering economic procedures to justify flexibility investments are abundant [see Kaplan (1986), Choobineh (1986), Meredith & Suresh (1986), Canada (1986), Falkner (1986.b), Park & Son (1988), Suresh (1990.b)]. The realization that traditional engineering economic procedures are barriers to investment in flexibility is only a symptom of the basic problem which is the difficulty in evaluating all true costs and benefits associated with this technology. This difficulty emerges because many of the advantages of flexible technology lie not in the area of cost reduction, but rather in more nebulous and *strategic* areas such as shorter lead times, increased quality and competitiveness. The benefits of flexible technology come from *tactical*, *operational* and *strategic* sources. Benefits coming from strategic sources can not be easily quantified. This has been referred as *quantification dilemma.* In addition flexible technology requires a high initial investment which results in high risk. As a result, notwithstanding many desirable benefits of flexible technology, flexibility investments have been difficult to justify.

Despite these criticisms of traditional engineering economic procedures, many experts believe that financial analysis is sufficient, and the use of traditional financial criteria is appropriate as long as they are correctly applied. Some authors conceive that economic justification should not be a barrier against flexibility investments because managers should be able to judge whether the gap between costs and quantifiable benefits is outweighted by anticipated nonquantified benefits [Kaplan (1986)]. Consequently, understanding all aspects of flexibility is important for managers who are engaged in decision making on strategic issues related to flexibility. In summary, economic justification procedures can be improved with a better understanding of flexibility and more active management participation.

Certainly, there is a need to modify traditional engineering economic analysis as well as to provide active management participation, for purpose of justifying flexibility investments. In particular, traditional cost accounting procedures are not able to provide the needed data. These procedures are not designed to report economic benefits from a more flexible system. Thus, there is also a need to deal with cost accounting problems.

In summary, during the development of justification procedures, the problems to be dealt with are the following:

1. Conceptual limitations of traditional techniques to consider all aspects of flexibility.
2. Accounting problems in order to asses all true costs and benefits of flexible technology.
3. Providing active management participation within the firms.

Conceptual limitations and accounting problems have been approached on a theoretical ground. Required modifications are being made depending on the situation, industry and manufacturing strategy of the firm. Within the firm a task force which consists of system engineers and managers can be formed in order to provide active organizational participation to justification. In fact, a task force should be constructed to play an important role as a committee of experts during installation and implementation as well as during justification. Then continuous performance improvement through organizational learning and experimentation can be achieved as Jaikumar (1986) argues. Therefore it is important to provide basic frameworks on understanding and justifying flexibility, which the task force can use as a basis for its expertise.

In recent years there have been significant developments in the theory of justification for flexibility investments. In general normative models on economic evaluation and justification of flexible technology fall into four groups; suggestions based on:

1. Simulation models,
2. Multi-Attribute decision models (**M**ulti-**A**ttribute **U**tility (MAU) theory and **A**nalytical **H**ierarchy **P**rocess (AHP)),
3. **M**ulti-**O**bjective **D**ecision (MOD) models.
4. **M**athematical **P**rogramming (MP) models, and

Chapter 4 provides a discussion of the recent literature on economic justification of flexibility investments. A special attention is given to three MP models: Fine & Freund (1990), Son & Park (1988) and Suresh (1989).

Over the last few years incremental implementation of flexible technology have been suggested as a remedy for the investment justification problems associated with the one-time installation of flexible technology. Because incremental implementation leads to lower capital outlays in each year. Furthermore incremental implementation instead of a one-time installation is more relevant in many cases since usually firms do not start from scratch. Suresh & Sarkis (1989) report that a majority of firms are believed to be adopting an evolutionary strategy of implementing flexible technology. According to them the poor linkage between corporate and manufacturing strategies have contributed to the slow adoption rates in case of a one-time installation. Actually, several U.S. firms were not able to achieve the performance targets due to the lack of experience in managing flexible systems. In many instances failure in performance is accompanied by a failure in attaining strategic payoffs of expensive flexible systems [Jaikumar (1986), Boer et.al. (1990)]. Incremental implementation however, may provide a more effective transition and absorption of flexible technology throughout learning and experimentation within the firms. Therefore the problem of incremental implementation and integration of flexible technology is being addressed formally in recent years.

Chapter 5 is aimed at developing a mixed-zero-one nonlinear programming, multimachine, multiperiod replacement model for incremental implementation of flexible automation investments. The model formulation is similar to Suresh (1989). Our suggestion is different from the earlier studies in that a new cost system suggested by Son (1991) is used and further refinements are provided in flexibility considerations. Finally, Chapter 6 consists of concluding comments.

Chapter 2

Understanding Flexibility

2.1 Importance of Understanding Flexibility and Scope of the Chapter

A large literature pertaining to flexibility in manufacturing has accumulated over the last decade. However, there still exist differences of opinion on the various ways to formalize the flexibility concept. Most authors [see Kumar (1986), Gupta & Buzacott (1988), Sethi & Sethi (1990), Chung & Chen (1989)] agree that the literature itself causes a confusion about formalizing and understanding flexibility in manufacturing.

Jaikumar (1986) states that with few exceptions, the flexible manufacturing systems (FMS.s) installed in United States show an **astonishing lack of flexibility**. He also emphasizes that the technology itself is not to blame, it is the **management** that makes the difference. Boer et.al. (1990) make a survey of the FMS.s installed in Netherlands and United Kingdom and point out the importance of flexible manufacturing system (FMS) **implementation management** to achieve the promises of FMS.s. According to Gupta & Buzacott (1988 the **lack of insight** on flexibility and the **inexperience** of manufacturing firms in managing flexible systems are among the primary reasons for the disparity between the promised and the actual performance of FMS.s. Primrose &

Leonard (1986) claim that **objectives** of the managers should be the focus of attention while **investing** and **managing** flexible technology. Due to the structural differences between companies, managers must be able to determine their requirements for their particular application. Therefore, managers should have a clear understanding of flexibility in order to identify their objectives. Then they can evaluate whether a **proposed** or an **existing** system meets these objectives.

Flexibility is emerging as a **competitive weapon** in today's manufacturing environment. It is widely accepted that flexibility is an important dimension of **manufacturing strategy** [see Verter & Dincer (1991), Fine (1990)]. Managers who are engaged in decision making on strategic issues related to flexibility need to know all benefits of capital intensive flexible systems. However, managers mostly measure benefits in dollars and it is hard to quantify many of the strategic benefits of flexible systems in monetary terms. The use of flexible technology can often be conceptually validated. In fact managers are usually expected to realize adequate returns from flexible technology without quantification. Consequently, it is important that top managers who are engaged in decision making on strategic issues, understand all aspects of flexibility.

Implementation of flexibility goes beyond the shop floor and permeates the business system of the firm. Furthermore, impementing flexible technology successively is associated with a learning curve. While the use of microprocessor technology is believed to be an important factor in achieving flexibility, careful planning and critical performance evaluation are necessary in order to be able to provide continual improvement throughout organizational learning and experimentation. Therefore, the role of operations managers in better implementing flexible technology should not be underestimated. It is essential however for the operations managers to understand all underlying aspects of flexibility in order to apply this technology in the right way.

We believe gaining insight into flexibility can lead to better **economic justification** as well as better **management**. Therefore throughout this chapter we give a review of the literature on formalizing the flexibility concept. We classify the conceptual frameworks as:

- **type based understanding of flexibility,**
- **change based understanding of flexibility.**

2.2 FMS.s and Flexibility

Browne et.al. (1984) define an **FMS** as *an integrated , computer controlled, complex of automated material handling devices and NC machine tools that can simultaneously process medium-sized volumes of variety of part types* [Browne et.al. (1984) p:1]. For any FMS:

- **computer control**
- **integration**
- **automation**
- **diversity of part types that can be processed**

are the key conceptual requirements. **Computer control** is used to monitor and coordinate the work stations and the material handling system. **Integration** is achieved by information processing; controlling the production of individual machines and reducing lead time and work-in-process. **Automation** is replacement of human performance tasks by machines in order to achieve efficiency while processing a variety of part types and increase quality. Automation also facilitates switching from one part type to another with reduced setup times. Therefore, FMS.s are widely regarded as a technological response to the ever-increasing customer demand for a wider diversity of products, faster product innovation, shorter delivery times and higher delivery reliability .

Actually FMS.s have been designed to attain the high productivity of well-balanced, machine-paced transfer lines, while utilizing the flexibility that the job shops have to process multiple part types simultaneously [see Browne et.al. (1984) & Huang & Chen (1986)].

Flexibility has been introduced as a property of FMS.s. In fact it is this property that distinguishes them from traditional high volume, process dedicated production systems like automated transfer lines. However, there is a common belief that a job shop itself is the most flexible system. Browne et.al. (1984) discuss the conditions under which a manufacturing system can be termed "flexible". They argue that systems can not be called flexible only because they produce a variety of part types or only they contain automated material handling. In the early 1980's many authors tried to define flexibility in order to distinguish FMS.s from other manufacturing systems [see Buzacott (1982) & Hildebrant (1980)]. Actually flexibility is the essential planned property of FMS.s, but it should be understood that *production systems that are not classified as FMS.s are not completely inflexible.* According to Gupta & Buzacott (1988) almost all production systems are flexible to certain degree. Thus, throughout this study our discussion on understanding and measuring flexibility is not restricted to FMS.s. In general we use FMS.s as examples and we mention flexibility investments or flexible technology referring to flexible manufacturing cells (FMC.s), flexible transfer lines (FTL.s), computer integrated manufacturing (CIM) systems as well as FMS.s.

2.3 An Early Definition of Flexibility

Mandelbaum (1978) defines **flexibility** as *the ability to respond effectively to changing circumstances.* He observes that flexibility in manufacturing is used in two different contexts. One relates to situations where the future is uncertain and a response may be required to an unexpected change. He calls this kind of flexibility ' **action flexibility** ', *the capacity for taking new actions to meet new circumstances.* That is leaving options open so that it is possible to respond to changes by taking appropriate actions. In to our opinion, action flexibility shows that flexibility is a design invariant under uncertainty as well as an attribute of a manufacturing system. Action flexibility is directly related to the design, limitations and physical properties of the system. However, it is indirectly affected by operating policies, attitudes of the managers and management practices. For example customers may ask for a new product. If the versatile machines in the system are able to produce the new product, the system has action flexibility. But the system may be so over scheduled that products can not be delivered in the proper time.

The other context relates to situations where the system is able to operate despite new circumstances. That is, the system has inherently action flexibility. This time our concern about flexibility is called state flexibility. Mandelbaum (1978) defines **state flexibility** as *the capacity to continue functioning effectively despite the change.* State flexibility refers to how effectively the system can cope with a change, while action flexibility shows whether or not the system is able to cope with it. For example, if the versatile machines in the system are able to produce a new product (i.e the system has action flexibility: can take the appropriate action) then the question is ' *what is the time required and money spent switching machines from one part mix to another?* '. Thus we conclude that selected performance criteria should be used while describing state flexibility. In the example given, above the performance criteria which are used to decide how effectively the system can respond to new product innovation is setup time and cost. Selecting appropriate performance criteria is a decision for managers based on their objectives and expectations from the system.

Similar to action flexibility, state flexibility is related to the design, limitations, and physical properties of the system as well as the operating policies, managers attitudes and management practices. For example, given a machine breakdown if the system can operate without increased work-in-process, this is due to the technological structure of the system, the proper scheduling of the jobs and the managers' attitudes with respect to increased work-in-process.

Action and state flexibility are both desirable for a manufacturing system. Increased action flexibility and increased state flexibility implies increased ability to respond effectively to changing circumstances.

Buzacott (1982) suggests that any attempt to understand and evaluate flexibility of a manufacturing system must begin with consideration of the nature of the changes and disturbances with which the system should be able to cope. He also advocates Mandelbaum's study (1978) and gives a classification of changes as:

- **external changes**
- **internal changes**

Notice that Mandelbaum (1978) and Buzacott (1982) point out a **change based understanding** of flexibility in order to clarify the effects of external and internal changes on the system. However, Buzacott (1982) also gives one of the earliest type classification of flexibility.

2.4 Type Based Understanding of Flexibility

Buzacott (1982) classifies flexibility into two types:

- **job flexibility**
- **machine flexibility**

Job flexibility refers to the *ability of a system to cope with changes in the jobs* and can be achieved by increasing operation capabilities of the system. **Machine flexibility** is defined as the *ability of a system to cope with changes and disturbances at the machines and work stations.* Buzacott (1982) states that the most common approach to achieve machine flexibility is through providing work-in-process inventories so that stoppage of one machine will not immediately force other machines down. However, this approach does not consider the negative effect of increased work-in-process inventories. Even though Buzacott (1982) emphasizes that all changes with which the system should be able to cope, should be considered, his flexibility classification only focuses on a small subset of changes.

There are many attempts in the literature to clarify what flexibility means. The purpose of these attempts is either to identify the benefits and key features of FMS.s that distinguish these systems from conventional systems or to measure physical characteristics and to monitor the effectiveness of these systems with respect to a given performance criterion [see Gerwin (1982), Browne et.al. (1982), Gupta & Buzacott (1988), Gold (1986), Son & Park (1987), Falkner (1986)]. Therefore several flexibility types have been defined along with the benefits that they suggest. Alternative measures for each flexibility type are provided.

Browne et.al. (1984) made the basic suggestion on classifying flexibility into types. They define and describe **eight type of flexibilities**, provide examples and explanations and also discuss measurement and attainability of each type. More specifically, Browne et.al. classify flexibility into:

- **machine flexibility**
- **process flexibility**
- **product flexibility**
- **routing flexibility**
- **volume flexibility**
- **expansion flexibility**
- **operation flexibility**
- **production flexibility**

and they also indicate the relationships among these types.

2.4.1 Flexibility Type Definitions

Sethi & Sethi (1990) provide a survey of the literature on flexibility types and report that at least fifty different terms for various types of flexibilities,*usually several terms referring to the same flexibility type*, can be found in the manufacturing literature. Since the definitions of these terms are not always precise and sometimes even identical terms differ in definition between authors; Sethi & Sethi (1990) do an excellent job of carefully defining many different types of flexibilities that have appeared in the literature. They also discuss each flexibility type in terms of its benefits. Furthermore, they give suggested measures for each flexibility type. They follow most closely to Browne et.al. (1984), but make modifications in order to standardize the terminology. Actually they go one step further from Browne et.al. (1984), although their study is far from being a detailed taxonomy of flexibility. Based on the rigorous study by Sethi & Sethi (1990), we give definitions, benefits and measures of **eleven flexibility types**. Table[2.1] provides a list of flexibility types under consideration.

Sethi & Sethi conclude that,

- *machine flexibility,*
- *material handling flexibility*, and
- *operation flexibility*

should be called **component flexibilities**, because these are the basic, important components of the production system. More specifically, machine flexibility is associated with the machines, material handling flexibility is associated with the material handling system and operation flexibility is associated with the parts to be processed. According to the type based understanding, the production level and technological structure of the system provide the basic framework to achieve flexibility. Therefore these flexibilities are necessary components for other flexibilities.

Table 1: List of Flexibility Types, Definitions, Benefits and Measures

Flexibility	Type :	Machine flexibility
	Definition :	Machine flexibility of a machine refers to the various types of operations that the machine can perform without prohibitive effort in switching from one operation to another.
	Benefits :	Allows lower batch sizes resulting in savings in inventory costs, provides higher machine utilizations, allows production of complex parts, provides shorter lead times for new product innovations.
	Measures :	*Number of different operations that the machine can perform without requiring more than a specified amount of effort. *Time and/or cost required to switch from one operation to another. *Ratio of the total output and the idle cost of a machine i.e. opportunity of a machine to add value to raw material. *Number of tools and programs that the machine can use
Flexibility	Type :	Material handling flexibility
	Definition :	Flexibility of a material handling system is its ability to move different part types efficiently for proper positioning and processing through the manufacturing facility it serves.
	Benefits :	Increases availability of machines and thus, their utilization and reduces throughput times.
	Measures :	*The ratio of the number of paths that the system can support to the maximal number of all possible paths in a system with the same number of machines
Flexibility	Type :	Operation flexibility
	Definition :	Operation flexibility of a part refers to its ability to be produced in different ways.
	Benefits :	Allows for easier scheduling of parts in real time, increases machine availability and utilization.
	Measures :	*Number of different processing methods for the fabrication of the part.

Table 1: continued

Flexibility	Type :	Process flexibility
	Definition :	Process flexibility of a manufacturing system relates to the set of part types that the system can produce without major setups.
	Benefits :	Reduced batch sizes and inventory costs, allows the machine to be shared and thus minimizes the need for duplicate or redundant machines.
	Measures :	*Volume of the set of part types that the system can produce without major setups. *The extent to which product mix can be changed while maintaining efficiency *Changeover cost between known production tasks within the current production program *Ratio of the total output and waiting cost of parts processed for a given period. *Number of all jobs that cannot be processed by the system multiplied by the probability that these jobs if fact will be required to be processed. *Expected value of a defined portfolio of products that can be processed through the system of limited resources for a given set of contingencies.
Flexibility	Type :	Product flexibility
	Definition :	Product flexibility is the ease with which the part mix currently being produced can be changed inexpensively and rapidly.
	Benefits :	Allows the company to be responsive to the market demand and provides competitiveness in the markets that are rapidly in flux due to the short and uncertain product life cycles.
	Measures :	*Time or cost required to switch from one part mix to another not necessarily of the same part types. *Ratio of total output to setup costs for a given period. *Number of new parts introduced per year. *Total incremental value of new products that can be fabricated within the system for a defined cost of new fixtures, tools and part programs.

Table 1: continued

Flexibility	Type :	Routing flexibility
	Definition :	Routing flexibility of a manufacturing system is its ability to produce a part by alternate routes through the system.
	Benefits :	Allows for efficient scheduling of parts by better balancing of machine loads and also allows to continue production when events such as machine breakdowns occur and thus contributes toward the strategic need of meeting customer delivery times.
	Measures :	*Average number of possible ways in which a part type can be processed in the system . *Ratio of existing number to possible number of links between machines in the given system. *Decrease in production when a machine breakdown occurs.
Flexibility	Type :	Volume flexibility
	Definition :	Volume flexibility of a manufacturing system is its ability to be operated profitably at different overall output levels
	Benefits :	Permits the factory to adjust production upwards and downwards within wide limits against uncertain demand and thus provides strategic advantage to survive when demand is increasing or decreasing.
	Measures :	*How small the volume can be for all part types together with the system still being run profitably. *The range of volumes in which the firm is profitable. *Ratio of average volume fluctuations over a given period of time to the production capacity limit. *Stability of manufacturing costs over widely varying levels of total production volume. *Amount slack capacity.
Flexibility	Type :	Expansion flexibility
	Definition :	Expansion flexibility of a manufacturing system is the ease with which its capacity and capability can be increased when needed.
	Benefits :	Allows step by step adoption of the system for expansion and thus it is important for firms which pursue growth strategies. Helps to reduce implementation time and cost for added capacity.
	Measures :	*Overall effort, time and cost needed to add given amount of capacity. * Ratio of cost of doubling the output of the system to its original cost.

Table 1: continued

Flexibility	Type :	Program flexibility
	Definition :	Program flexibility is the ability of the system to run virtually untended for a long enough period.
	Benefits :	Reduces throughput time by having reduced setup times, improved inspection and gauging and better fixtures and tools. Provides tighter tolerances and thus better quality. Being able to work untended increases effective capacity. Also allows simultaneous improvement of productivity and quality which have strategic importance.
	Measures :	*Expected percentage uptime during second and third shifts.
Flexibility	Type :	Production flexibility
	Definition :	Production flexibility is the universe of part types that the system can produce without adding major capital equipment.
	Benefits :	Provides competitiveness in a market where new products are frequently demanded. Minimizes implementation time and cost for new products or major modifications of existing products. Permits an increase of part families.
	Measures :	*Size of the universe of part types which the system is capable of producing.
Flexibility	Type :	Market flexibility
	Definition :	Market flexibility is the ease with which the manufacturing system can adopt to a changing market environment.
	Benefits :	Provides survival in environments that are constantly in flux. Allows the firm to respond to rapid changes in technology, customer tastes and product life cycles. Enables the firm to cash in on new business opportunities and thus, it is a competitive weapon.
	Measures :	*Time and cost required to introduce a new product, to increase and decrease production volume by a specified amount *Shortage cost or the cost of delay in meeting customer demand.

In a similar fashion,

- *process flexibility,*
- *routing flexibility,*
- *product flexibility,*
- *volume flexibility,* and
- *expansion flexibility*

are called as **system flexibilities** and

- *program flexibility,*
- *production flexibility,* and
- *market flexibility*

are called as **aggregate flexibilities**. System flexibilities and aggregate flexibilities apply to the manufacturing system as a whole.

Sethi & Sethi (1990) point out that a **sophisticated computer and information technology** and a **flexible organizational structure** underlie each flexibility type. It is because of this technology that flexibility in manufacturing has become possible without a considerable sacrifice in efficiency.

Evidently machine flexibility can be achieved by having versatile NC machine tools. Material handling flexibility can be achieved by having devices such as automated guided vehicles, robots and computer control. Operation flexibility is directly related to the design of part types. Generally speaking, component flexibilities can be achieved by an appropriate design. Moreover, component flexibilities can be viewed as independent from each other and are directly related to the technological specifications of the system. However, system flexibilities can not be achieved without having component flexibilities. For example, product flexibility depends on the operation capabilities of the machines, the structure of the material handling system and, the design of the parts as well as on the availability of the machines (i.e. proper scheduling). Similarly, aggregate flexibilities can not be achieved without having system flexibilities and the support of an appropriate organizational structure. Thus, there are several implicit and explicit interrelationships between flexibility types, and microprocessor technology, and the organizational support structure.

2.4.2 Interrelationships Between Flexibility Types

Actually, flexibility is a **multidimensional** concept. Because of this multidimensional nature many flexibility types have been identified. However, if flexibility types are viewed as dimensions of flexibility, then obviously these dimensions are not independent. First of all component flexibilities constitute a basis for other flexibilities. This is because component flexibilities are associated with the production unit of the system, and the production level provides the framework to achieve flexibility. As a result, **technological specifications** which effectively coordinate the machines, material handling system, and the part types are very important, and a **microprocessor technology** should be utilized to achieve flexibility without sacrificing efficiency.

One indicator of these interrelations can be found by examining the measures in Table[2.1]. The ration of the number of ' paths ' to maximal number of paths is essentially the same as the same ration for ' links ' yet one claims to measure material handling flexibility and the other routing flexibility. A market flexibility measure suggested is the time and cost to change production volume. Isn't this really volume flexibility?

The interrelationships and dependencies between flexibility types cause flexibility to be a **complex** concept. Sethi & Sethi (1990) developed a diagram (see figure[2.1]) to show dependencies between flexibility types which extends the one developed by Browne et.al. (1984). The diagram indicates that component flexibilities contribute to various system flexibilities. These in turn influence the aggregate flexibilities as shown. Viewed from another perspective, the aggregate flexibilities, which are closely associated with the firm's manufacturing strategy, dictate the extent of system and in turn, of component flexibilities that the firm must possess.

Figure[2.1] illustrates that flexibility types have a hierarchical structure. Moreover, this hierarchical structure is directly related to the hierarchical structure of the system. Since there are many linkages between different hierarchical levels of the system, interrelationships between flexibility types are observed. However, the interactions between the hierarchical levels of the system are not easily determined. Similarly, the interactions between flexibility types are not obvious. This is why flexibility is a complex concept. Furthermore flexibility is affected by a number of factors like operating policies, management practices and technological specifications of the system. As a result, a **flexible organizational structure** is required to achieve flexibility [Ettlie (1986)]. But it is not easy to foresee the full effect of operating policies, management practices, and technological specifications on flexibility. And this makes the concept much more complex.

In an excellent article, Carter (1986) states that it would be desirable to classify flexibility into types in a way that each could be considered independently. This would simplify analysis and design, but does not seem possible. Carter (1986) suggests that the advantages provided by flexibility and the timeframe in which they occur are both key factors in gaining insight into flexibility. Different flexibility types affect the system on different timeframes. This is equivalent to saying that each flexibility type provides some advantages to cope with specific changes and these changes occur on different timeframes. We have already stated that flexibility types have a hierarchical structure and this hierarchical structure is related to the system hierarchy. In later sections we conclude that advantages provided by flexibility and changes to be coped with also show hierarchical structures which are related to the system hierarchy. Therefore we now analyze flexibility from another perspective which appears to give a better insight into the multidimensional and complex natures of flexibility.

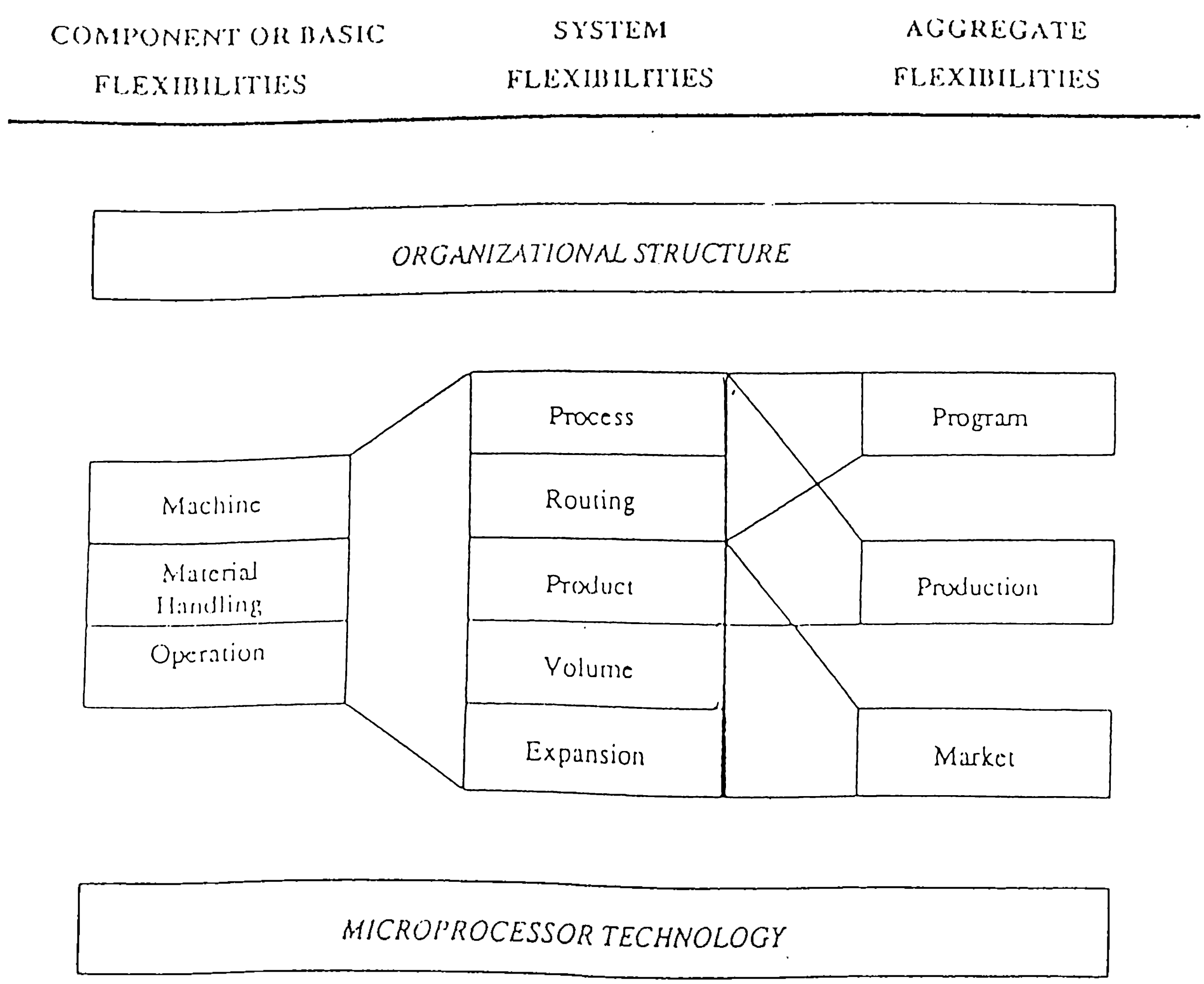


Figure 2.1: Interrelationships Between Flexibility Types: Sethi & Sethi (1990)

2.5 Change Based Understanding of Flexibility

2.5.1 Advantages of Flexibility and Timescale Decomposition of Changes

Carter (1986) states that each flexibility type affect production in different timescales. A rough categorization of timescales is given by :

- short term,
- medium term, and
- long term.

According to Gupta & Buzacott (1988) short, medium and long term timescales can not be defined precisely, because these terms could imply different timescales for different industries. For example, short term may mean a few hours for a job shop, but only a few seconds for an electronic assembly operation. Actually these timescales are a function of industry, market strategy, supplier network of the firm, etc.

Carter (1986) defines the timescales in terms of several major processes that take place, such as the time to process a change order or to purchase a new equipment. He suggests that there are incentives for making a manufacturing system flexible and presents a list that indicates which flexibility type affects production, on which timescale, and what kind of incentives are provided. From another perspective, each flexibility type provides some advantages, and these are utilized in different timescales (see Table [2.1]). For example, the competitiveness advantage due to product flexibility can be utilized in the long run, while efficient scheduling provided by routing flexibility is utilized in medium term. Many authors have attempted to identify these advantages of flexibility [see Jaikumar (1986), Goldhar & Jelinek (1985), Huang & Chen (1986), Choobineh (1986)]. Most of these authors agree that advantages of flexibility come from three sources:

- tactical,

- **operational, and**
- **strategic sources**

Advantages due to tactical sources mostly can be utilized in short term and thus are called **short term advantages**. In a similar fashion, advantages due to operational sources mostly can be utilized in medium term and thus are called **medium term advantages**. Advantages due to strategic sources can be utilized in long term and thus called **long term advantages**.

Remembering the definition of flexibility suggested by Mandelbaum (1978) the advantages, that flexibility provides, are to respond effectively to changes. Carter (1986) emphasizes that advantages provided by flexibility and timescale in which these advantages can be utilized are key factors to understand flexibility. Actually each flexibility advantage can be utilized in different timescales. This is because, an advantage is only utilized when a change occurs and changes occur in different timescales. Therefore a timescale decomposition of changes provides the key to understanding flexibility:

- **short term changes,**
- **medium term changes, and**
- **long term changes.**

Gupta & Buzacott (1988) provide definitions and give examples of short, medium and long term changes. **Short term changes** may be effective for a few minutes to a few hours. Frequent short term changes might cause significant production losses in the long run. Variability of machining times and equipment breakdowns are the examples of short term changes. **Medium term changes** may have a timescale ranging from a few days to a few months. A change in the monthly demand of a certain product, where the long term average demand does not change, is an example of a medium term change. Again frequent medium term changes affect production significantly in the long run. On the other hand, **long term changes** occur quite infrequently and may be effective over a period ranging from a few months to a few years. For example, the introduction of new products and the development of new raw materials are long term changes. Notice that the terms short term, medium term or long term could imply different timescales for different industries depending on other parameters, like processing times.

Any manufacturing system should be able to respond to changing circumstances in order to survive and compete in the long run. Short term advantages of flexibility can be utilized when the system meets short term changes. Similarly, medium and long term advantages of flexibility can be utilized for medium and long term changes respectively. As a result flexibility with its suggested advantages, provides system survival and competitiveness in the long run.

2.5.2 Change Based Definitions of Flexibility

The definition of flexibility suggested by Mandelbaum (1978) is a change based definition. After Mandelbaum (1978), **flexibility** is widely accepted to imply *ability of a system to cope with changes* [see Gupta & Buzacott (1986)]. According to Gupta & Buzacott (1988) this definition does not explain what ability means and is hard to operationalize. Thus, they introduce two important aspects of the term **ability**; namely: **stability** and **sensitivity** in attempting to overcome this difficulty.

Sensitivity relates to the degree of change tolerated before a deterioration in **performance** takes place. In other words, *sensitivity determines whether or not a response is needed when a change occurs.* If the system is sensitive to a change, that is if a response is needed, then its **stability** relates to the size of each disturbance for which the system can meet **performance** levels expected of it. In the above statement size of disturbance refers to both number of different types of changes and the magnitude of each change that the system can respond to. Briefly, *stability determines whether or not the system is capable of responding given that a response is needed.* Gupta & Buzacott (1988) conclude that reduced sensitivity with respect to a given change implies that the system performance is not affected despite the change. On the other hand, increased stability implies that the system can respond to various changes when a response is required.

Note that while defining both sensitivity and stability the term 'performance' has a special importance because they are a function of **how well** the system copes with changes. Gupta & Buzacott (1988) state that 'how well' is measured in terms of performance criteria such as the production loss during the time taken to respond to a change and the cost of response. Thus Gupta & Buzacott (1988) give a variation of the popular definition which embodies the idea that a good performance is expected from the system besides flexibility. They define *flexibility* as the ability of a system to cope with changes **effectively**.

We suggest that flexibility has not only two but three different aspects: sensitivity, stability and effectiveness. We combine the effectiveness aspect into the stability aspect. Therefore we define **stability** as *how well the system responds to a change given that a response is needed.*

For example, a system whose performance is not affected by machine breakdowns is less sensitive than another system that is affected by such changes. Thus, sensitivity is not really a desired property. A system, whose performance is affected by tool wear and which is capable of responding to tool wear without *increased defects*, is more stable than another system affected by tool wear. Similarly, a system capable of making correction for tool wear as well as tool failure, without *increased defects* and *work-in-process*, is more stable as compared to a system that responds to tool failure only. Thus stability is a desired property. Notice that, after combining effectiveness aspect into stability aspect,*amount of defects* or *work-in-process* or both may show the stability level of the system.

In our opinion, the stability level of a system subject to a given change can be measured by performance criteria and this can be viewed as flexibility measurement ' for the change '. Thus stability level expected from a system will depend on the selected performance criteria and managers' attitudes and preferences. If the selected performance criterion

SENSITIVITY : whether or not a response is needed when a change occurs.

Sensitivity =
- 0, a deterioration in performance does not take place, i.e. a response is not needed.
- 1, a deterioration in performance takes place, i.e. a response is needed.

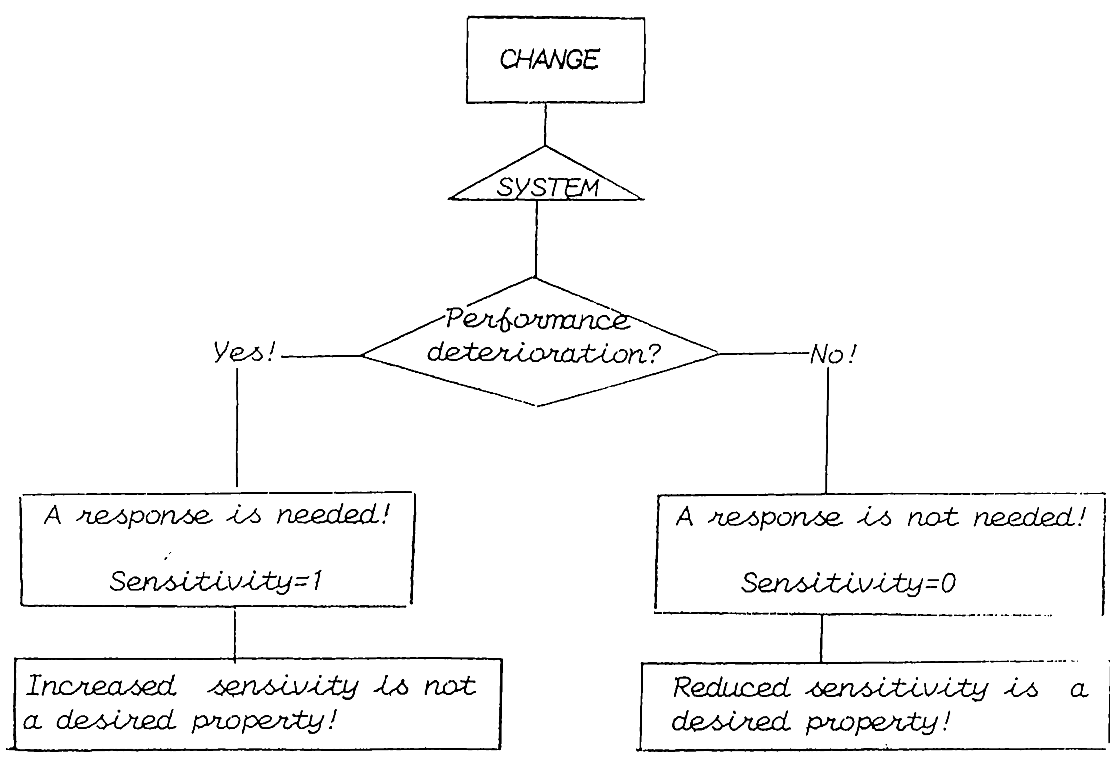


Figure [2.2] Sensitivity

Gupta and Buzacott (1988) :

STABILITY : Whether or not system is able to respond given that a response is needed.

$$\text{Stability} = \begin{cases} 0, & \text{system is not able to respond given that sensitivity=0.} \\ 1, & \text{system is able to respond given that sensitivity=0.} \end{cases}$$

Our Suggestion:

STABILITY : How well the system responds to a change given that a response is needed.

STABILITY IS MEASURED BY SELECTED PERFORMANCE CRITERIA

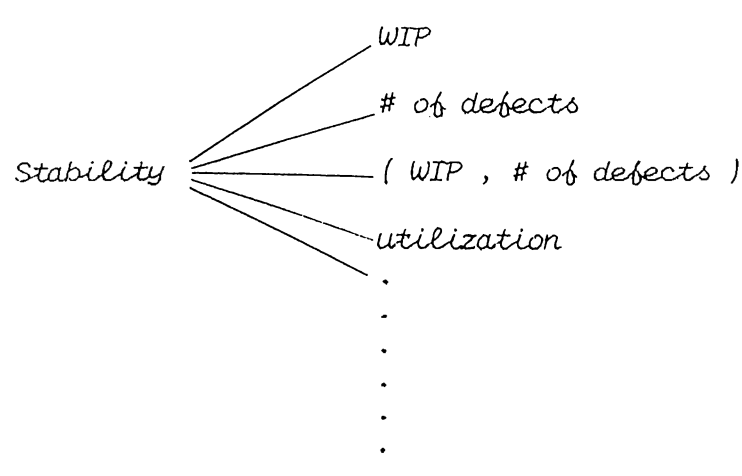


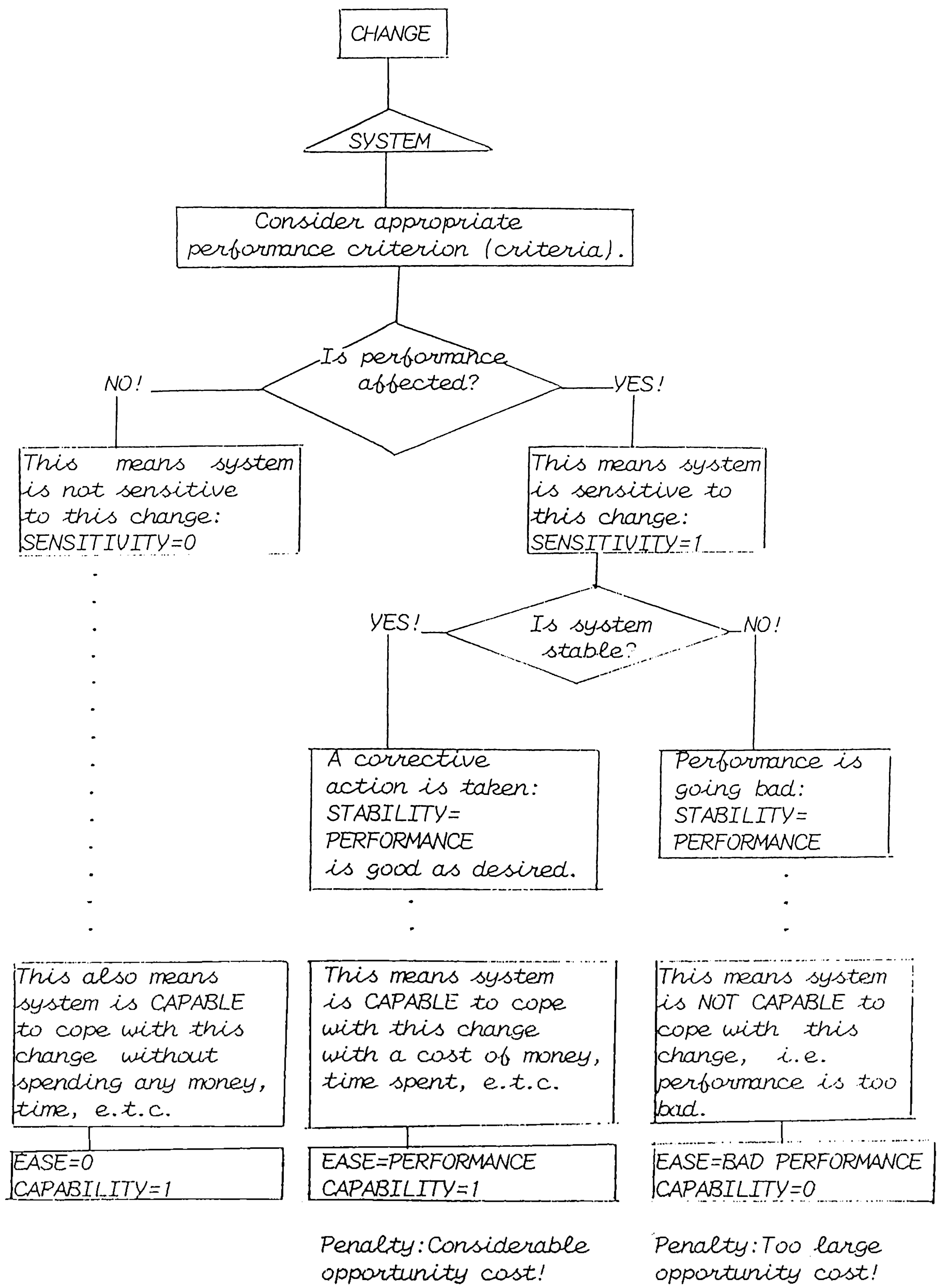
Figure 2.3 Stability

is number of defects, then less defects implies higher stability. When the selected performance criterion happens to be work-in-process then reduced work-in-process implies higher stability, unless the managers think that work-in-process provides safety against machine stoppage. There may two or more different selected performance criteria. For instance higher stability might require both reduced work-in-process and less defects.

On the other hand, by its definition, sensitivity of a system subject to a given change can be represented by a 0-1 variable. That is, if system performance is affected by a change then system sensitivity is 1, otherwise is 0. Since a deterioration in performance is not desired, greater sensitivity is not desired either. If system sensitivity is 1 for a given change, then system stability level subject to that change can measured by selected performance criteria. Stability is a desired property because greater stability implies that the negative effects of a performance deteriorating change can be properly mitigated. In brief, decreased sensitivity and increased stability imply increased flexibility i.e., ability to cope with changes effectively. This observation gives an idea about the prevailing discussion among the researchers on how flexibility relates to the system performance.

Notice that both sensitivity and stability are defined in a way that each is associated with *a given change*. Usually there are many changes to be coped with. For each change one must consider sensitivity and stability, i.e. the ability to cope with that change. Since there are many changes, there are many abilities for responding those changes. Different abilities for coping with different changes constitute the **multidimensional** nature of flexibility.

Sensitivity and stability associated with manufacturing flexibility are influenced by several factors like *characteristics*, *physical properties* and *design of the system*, *operating policies*, *management practices* and *the attitudes of the managers*. For example, an *over scheduled* system shows sensitivity to machine breakdowns. As a result, a significant production loss may occur if the system can not take a corrective action to maintain stability. However, if there is a duplicate machine as a design input and if it is available then depending on the operating policy the system may not show sensitivity against breakdown. When a



sensitivity=0 $\Longrightarrow$ ease=0 and capability=1

capability=1 $\Longrightarrow$ sensitivity=0 or system is stable

Figure 2.4 Sensitivity-Stability and Capability-Ease performance deteriorating change occurs, a corrective action is taken depending on the past experience. Thus stability depends on management practices. Furthermore, since stability can be maintained according to a selected performance criterion, the *attitudes* and *preferences of the managers* are vitally important for achieving the flexibility expected from the system. The effects of above listed factors on sensitivity and stability helps to explain the **complex** nature of flexibility.

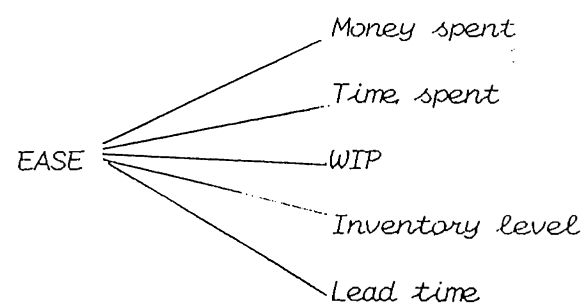
From this perspective, the performance of two systems (for a selected performance criterion) having different ranges of sensitivity and stability are comparable, contradicting Gupta & Buzacott (1988). Figure [2.4] illustrates how sensitivity and stability notions can be used to evaluate the performance of a system for selected performance criteria subject to a given change. While comparing performance of two systems for a given change and selected performance criteria, the system whose sensitivity is zero is preferred. If both systems have sensitivity equal to one, then their performance is compared according to the selected performance criteria. In the next sub-subsection we discuss another definition of flexibility and present *capability and ease* concepts which are similar to *sensitivity and stability.*

2.5.3 An Operational Definition of Flexibility

Suresh (1990.b) adopts the following general notion of flexibility:
Flexibility *is the* **capability** *as well as the* **ease** *with which a change can be accommodated by a manufacturing system.*

Capability associated with a given change can be represented by a binary valued parameter. This means the system is either capable to accommodate the change easily or not. Here the word *easily* corresponds to *how well* the system copes with the change. Now it should be noted that the ease associated with a given change can be represented by relevant time, cost and other measures (see figure[2.5]).

Ease is measured by performance criteria:



Suppose EASE is measured by money spent to accomodate a given change. Let A be maximum amount that can be spent. Then:

$$\text{CAPABILITY} = \begin{cases} 0, & \text{if system is not capable to accomodate the change easily, i.e. money spent} > A. \\ 1, & \text{otherwise, i.e. money spent} < A. \end{cases}$$

Figure 2.5 Capability and Ease

Suppose a machine breakdown occurs. If the broken machine can be repaired without spending too much time, then we say that the system is capable to cope with this change easily. The time spent shows the level of ease. In fact, it is the level of ease that determines whether or not the system is capable to cope with the given change. In this example, if the repair time required is more than the available time, we say that the system is not capable to cope with machine breakdown easily. We propose figure[2.6] as an illustrative framework that uses capability and ease notions for understanding flexibility and call this framework as *capability-ease approach for understanding flexibility.* Actually understanding flexibility with sensitivity and stability is essentially the same as understanding flexibility with capability and ease. Figure[2.4] explains the relationships between sensitivity-stability and capability-ease.
Capability and ease are defined so that they are associated with a given change. For each change capability and ease must be determined. If a system is capable with respect to many changes then we call that system as flexible.

A system which is capable to accommodate all changes easily is an hypothetical system. If there exists such a system, its initial cost will certainly be too high. However, it seems unlikely that we could design a system which is capable to accommodate all changes easily because each system has pros and cons. In order to obtain the appropriate system, managers should know the kind of changes to be coped with. This means managers should know what they require in their particular application. This is the subjective aspect of flexibility.

2.6 Summary

Understanding flexibility is made difficult by its multidimensional nature and the attempts to classify aspects of flexibility into ' types ' are aimed at dealing with this dimensionality problem. However a flexibility type definition is really a cursory classification of anticipated changes followed by the selection of performance measures which indicate the effects of the changes on the manufacturing system.

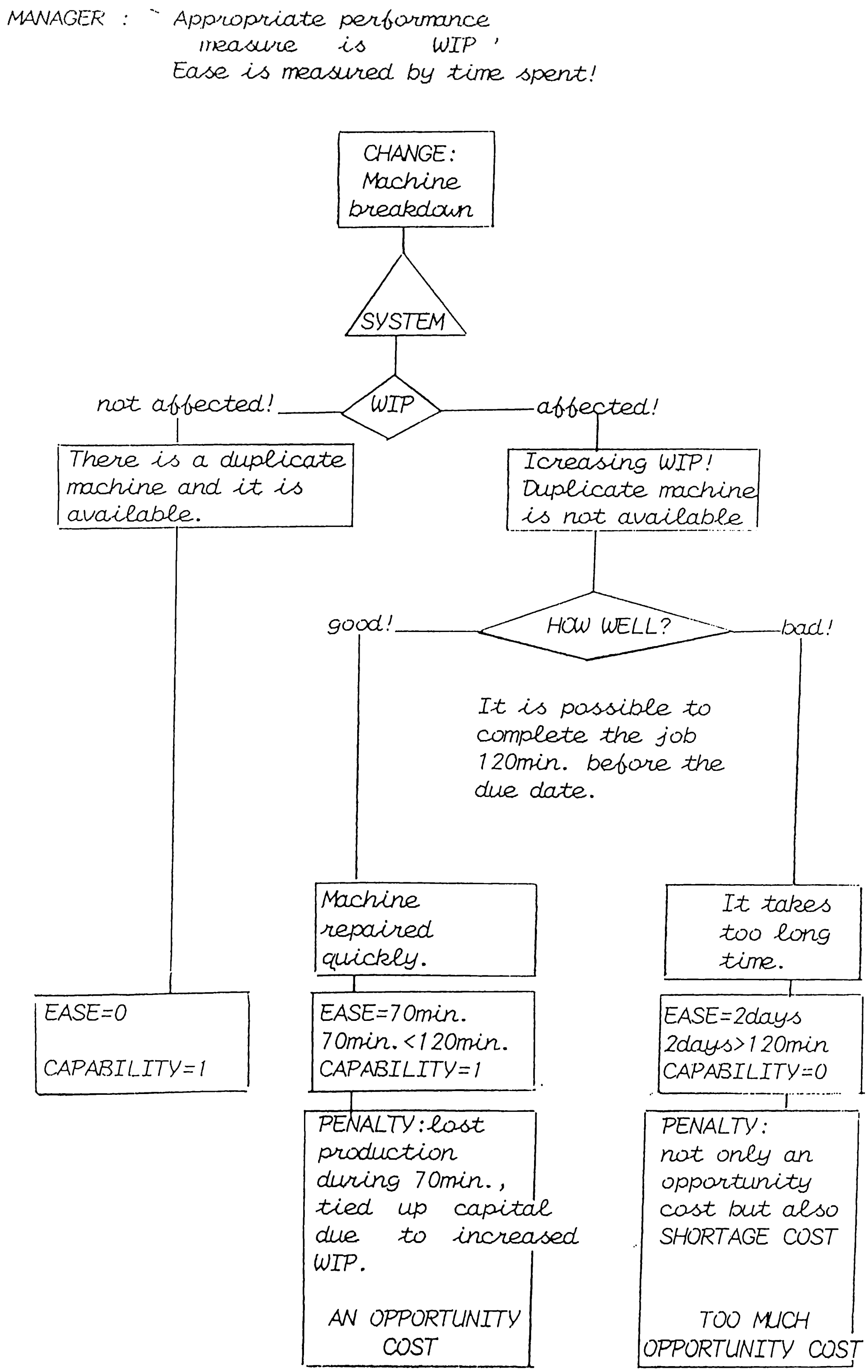


Figure 2.6 CAPABILITY-EASE APPROACH

Since everyone agree that flexibility is the ability to cope with change a more direct approach seems warranted. First identify the potential changes against which some degree of protection is desired and then identify the relevant performance measures. We feel this change based approach will provide greater understanding of flexibility to managers. We expand Suresh's (1990.b) capability and ease definition to provide a basis for a better understanding and show that it is identical to Buzacott & Gupta's (1988) sensitivity and stability concepts for understanding flexibility, if the definition of stability is changed slightly to include the notion of effectiveness. In subsequent chapters we will argue that the capability-ease concept has more promise than the other suggestions for the purposes of flexibility measurement and the justification of advanced manufacturing systems.

Chapter 3

Measuring Flexibility

3.1 Why measure Flexibility ?

Flexibility is:

- a **DESIGN INVARIANT** under uncertainty,
- a **COMPONENT OF MANUFACTURING PERFORMANCE**,
- an **ATTRIBUTE** of a manufacturing system.

Flexibility is a DESIGN INVARIANT under uncertainty:

Flexibility is a hedge against uncertainty. Thus it can be viewed as a design invariant under uncertainty. However, while articles citing expected benefits from flexible technology are abundant, some companies' experiences have shown that the actual performance of this technology may not achieve expectations. Actually these failure stories can be viewed as the symptom of the basic misunderstanding that flexibility is a *panacea.* For an optimal design, understanding flexibility is critical in order to determine the extent of automation, especially in a labor intensive environment such as Türkiye or when some other alternative technology exists. Even though understanding flexibility is necessary for predesign, it is not sufficient for success. Because flexibility is a design invariant under uncertainty, there is a need to measure flexibility in order to guide design specifications.

Flexibility is a COMPONENT OF MANUFACTURING PERFORMANCE:

Poor actual performance of flexible technology is often due to implementation management. The lack of insight on flexibility and the inexperience of firms in managing flexible systems are usually among the primary reasons for this problem. Even if an appropriate design is selected, a performance deterioration may be caused by management due to the lack of a feedback mechanism. Monitoring the effectiveness of the system after installation is a basic requirement for successful implementation. Success stories on flexibility investments can not completely be credited to the mere introduction of hardware and software. Because adopting flexible technology is associated with a learning curve, continual improvement on this curve can only be achieved by close evaluation of system performance. Since flexibility is a critical component of manufacturing performance, there is a need to measure and evaluate flexibility of the system. Flexibility measurement can facilitate whether or not the expected level of flexibility and its benefits are achieved, and also can provide a valuable tool to be used by operations managers to reach promised performance levels. This explains why measuring flexibility is crucial for operations managers who are interested in achieving continual improvement and providing all advantages of flexibility during implementation. Thus we can say that if flexibility is widely understood and if its measurement can be ascertained in a way that is meaningful to the managers, then flexible technology can be implemented more successfully.

Flexibility is an ATTRIBUTE of a manufacturing system:

Flexibility is emerging as a competitive weapon in today's manufacturing environment and it is accepted to be an important dimension of manufacturing strategy. It is well documented that flexibility investments can easily fail economic justification owing to the lack of techniques to quantify all benefits of flexibility. Flexibility makes economic sense only if all true costs and benefits can be included in a justification procedure. Measuring flexibility, at least facilitates the use of techniques like the Analytic Hierarchy Process and Multi-Attribute Utility models for evaluating investment alternatives. These methods may promote investment in flexible technology. Flexibility can be viewed as a factor in the strategic managers' decisionmaking about a flexibility investment. Consequently, measuring flexibility is also a concern to these strategic managers as an aid to effective decisionmaking on strategic issues. If flexibility measurement can be specified in a way that is meaningful to strategic managers, then it is more likely to be incorporated in manufacturing strategy.

Summarizing, there is a need to measure flexibility in order to:

- guide design specifications,
- evaluate investment alternatives, and
- set performance goals and achieve continual improvement.

3.2 Flexibility Measures in the Literature

Due to the increasing recognition of importance of flexibility in design, decision-making, planning and implementation, there have been a number of suggestions for measures of flexibility. Based on a detailed review of the literature, we find that these measures are based on flexibility ' type ' definitions [see Buzacott (1982), Chatterjee (1982), Browne et.al. (1984), Carter (1986), Jaikumar (1986), Son & Park (1987), Suresh (1989)]. Performance measures for each flexibility ' type ' are derived based on its definition. Different researchers have emphasized different flexibility ' types ' and consequently have often suggested different measures. Thus this widespread divergence of opinion about flexibility points out the importance of first understanding this concept. This means, all underlying aspects of flexibility, its multidimensional and complex natures should be well understood in order to measure flexibility.

A comprehensive list of flexibility type measures that have appeared in the literature, as reported in the survey article by Sethi & Sethi (1990), can be found in table[2.1]. The flexibility measures indicated in table [2.1] suggest that the literature to date has looked at flexibility from a rather narrow angle and has focused only specific aspects of flexibility. In brief, most of these measures suffer from the following limitations:

- They tend to be *nonfinancial* measures. Only a few are in monetary terms; such as the cost of switching from one product to another, or the total incremental benefits of new products to be fabricated. Thus they are not operational for the use of managers.
- They are not global but *local* measures. They tend to look at the manufacturing system from a rather narrow angle and ignore the importance of interrelationships between flexibility ' types '.
- They are *isolated* measures in that they are derived independently of the environment in which the manufacturing system functions. They focus on the physical characteristics of the system and generally ignore the effects of factors such as operating policies and managers attitudes.

Chung & Chen (1989) emphasize that there is a pressing need to develop an explicit analytical framework for understanding flexibility from a holistic viewpoint. They believe this is prerequisite to a better assessment of the value of system flexibility. In their survey, Sethi & Sethi (1990) find that very little work has been done to develop analytical models that rigorously deal with the measurement of flexibility. This explains why flexibility measurement is still and should be an area of current research.

Flexibility measurement can be approached in two ways:

- **measuring flexibility as a single value** (total system flexibility),
- **measuring the effect of flexibility on system performance for different performance criteria.**

In the following subsections these are discussed in detail and our conclusions are:

- Measuring flexibility as a single value appears to be impossible.
- There is promise for future research on measuring the effect of flexibility on system performance and finding an answer to the question how flexibility relates to the system performance.

3.3 Measuring Flexibility as a Single Value

As discussed in Chapter 2 both type based and change based approaches contribute a great deal understanding the multidimensional nature of flexibility. The origin of the problem of measuring flexibility as a single value is the curse of dimensionality that is unique orderings do not exist for dimensions greater than one. If A & $B \in R^1$ then $A < B$ or $B < A$ can easily be determined. However if A & $B \in R^n$ for $n \geq 2$ then one must select from numerous mappings of the vectors A & B into R^1 (i.e. based on vector magnitude, selection of a single coordinate or using utility functions) so that A & B can be ordered.

Whether one adopts the type-based or the change-based understanding approach when considering a manufacturing system, the end result is a set of performance measures , P. The $p_i \in P$, $i = 1, 2, .., n$ represent a vector, where each coordinate may be measured in different units (time, cost, number, ratio) and on different scales. The problem of measuring flexibility as a single value is thus one of finding a meaningful transformation of this vector into R^1. There are a host of other problems:

1. For each p_i , how does one determine the range of scale such that the end points represent minimum and maximum ability to cope with change? That is, is p_i representative of the system's flexibility?
2. Is the set P realistic in the sense, does it truely represent the flexibility of a particular manufacturing system?
3. Is there a set P which is comprehensive in the sense, does $\exists$ a vector $p_i \in P$ which is realistic for any manufacturing system to be measured, from a flexible cell to an

entire factory?

The first question requires empirical research and is outside the scope of this thesis. We assume the answer is positive and that P is realistic with respect to the manufacturing system under consideration. Later we will claim that the change-based approach is more likely to generate a realistic P then is the type-based approach.

A universal flexibility measurement model can be found only if there is a P which is comprehensive. This seems unlikely when one considers the effect on a corporate strategy of a CNC machining center versus a flexible assembly plant. The differences are perhaps too great. It may be that there exist several P's, each applicable at different manufacturing levels. However, since there has been essentially no empirical measurement of flexibility, this will remain an open question.

We define total system flexibility, (TSF) as the resulting flexibility from the aggregate effect of performance measures p_i which are to be incorporated into the system evaluation. Performance measures p_i represent the dimensions of flexibility. From theoretical point of view there exist three different methods of dealing with the dimensionality problem to combine the nonhomogeneous performance measures into a single dimension to obtain the value for TSF:

1. Multi-Attribute Utility (MAU) models,
2. Analytic Hierarchy Process (AHP), and
3. Entropy Theory.

3.3.1 MAU Models

Managers can play a very important role as decisionmakers while assessing the value of TSF if MAU models are used as the class of mappings which transforms the multiple dimensions of TSF into a single dimension. Thus, probably the best way to transform the relevant dimensions of TSF is the MAU analysis, because the level of TSF that the system should and does possess is best assesed by the managers. Furthermore MAU analysis does not necessarily require a hierarchy for the purpose of defining P.

In most of the models developed for justification based on MAU analysis, there is at least one attribute that represents flexibility. But nobody has attempted to measure flexibility as a single value. Falkner & Benhajla (1990) defined a surrogate performance measure set to include measures representing of flexibility. This study is discussed in Chapter 4. However even for justification purposes no universal model is possible using MAU analysis. This is because two firms could develop vastly different models for the same system due to the subjective judgements involved. The model developed can evaluate a single system and thus can be used for design and performance evaluation.

3.3.2 AHP

AHP requires a hierarchy and thus best suited to P defined by flexibility types [see figure(2.1)]. If P is defined by change based approach, too many first level nodes need to be considered. AHP is not suited for design and performance evaluation because it requires pairwise comparison of alternatives at bottom level. Arbel & Seidmann (1984) applied AHP for the justification of an FMS and considered different aspects of flexibility in their hierarchy. But they did not attempt to measure flexibility as a single value.

3.3.3 Entropy Theory

Kumar (1986) suggested to use entropy theory for measuring flexibility as a single value. This approach does not have the limitations of MAU and AHP models, however needs emprical validation.

3.3.4 More on Single Value Measurement

It could futher be argued that a single measure of flexibility is unlikely to emerge owing to the following reasons:

1. **Flexibility is multidimensional**; implying that flexibility is a function of

   - physical components of the system
     (machines, material handling system, parts to be processed) ,
   - properties and organization of the physical components
     (operations that can be done, layout of the system, production volume) ,
   - industry
     (continuous process, batch production process) ,
   - customers and overall market demand
     (portfolio of products to be produced, fluctuations in market demand).

   In fact, all the above items are referred to within the flexibility types. Effects of these items come from different sources and thus, it is unlikely that their aggregate effect can be represented by a single measure.

2. **Flexibility is complex:** Flexibility is also a function of factors like,

   - operating policies,
   - management practices, and
   - managers' attitudes and preferences.

However, it is not easy to quantify the effects of operating policies and management practices with meaningful measures. Moreover each of the above listed factors affect each other. That is there are several interrelationships between the dimensions of flexibility. Thus it is unlikely that a single measure which captures all aspects of flexibility will emerge.

3.4 Measuring the Effect of Flexibility on System Performance

Buzacott (1982) states that while quantitative approaches to measuring flexibility need to be investigated further, thinking about flexibility in a formal way provides useful and helpful insights. However, our discussion on flexibility has stressed the idea that understanding flexibility is a prerequisite to developing more rigorous analytical models for flexibility measurement. Perhaps both approaches are needed simultaneously in order to evolve to a widely accepted theory of flexibility.

Measuring the effect of flexibility on system performance means choosing one component p_i of P and then attempting to relate the other components of performance to it. This is the quantitative modeling approach. For example, justification of flexibility investments can be viewed as measuring the effect of flexibility on system performance where system performance is measured by the profitability of manufacturing operations. Thus modeling the economic impact of flexibility is one approach to the justification problem. The models suggested by Park & Son (1988) and Suresh (1989) discussed in depth in the next chapter are excellent examples of this approach. Excluding justification approaches there are only a few attempts to monitor the effectiveness of flexible systems with respect to a given performance criterion like productivity, quality, reliability, ..., etc. These will be discussed below.

3.4.1 Gupta & Buzacott (1988)

Carter (1986) advocated using the timeframes to gain insight into flexibility. He classified the ' types ' of flexibility by the timeframes in which they affect production. Gupta & Buzacott (1988) proposed a variation of this classification, where changes and not types of flexibility are categorized according to timeframes. Remember, Gupta and Buzacott (1988) conceive that flexibility is the ability of a system to cope with changes effectively where the word ability refers to both sensitivity and stability. Following this definition of flexibility and a timescale decomposition of changes, three dimensions (or types) of flexibility emerge:

- **Short term flexibility:** Reduced sensitivity, increased stability against short term changes for a specified performance criterion $p_s \in P$. This dimension is represented by short term advantages of flexibility.
- **Medium term flexibility:** Reduced sensitivity, increased stability against medium term changes for a specified performance criterion $p_m \in P$. This dimension is represented by medium term advantages of flexibility.
- **Long term flexibility:** Reduced sensitivity, increased stability against long term changes for a specified performance criterion $p_l \in P$. This dimension is represented by long term advantages of flexibility.

Aggregation of values of short, medium and long term flexibilities constitutes the measure of flexibility. However the curse of dimensionality remains. Gupta & Buzacott (1988) propose a scheme for measuring flexibility with respect to this timescale decomposition of changes. In their view measure of flexibility comes from performance models for short and medium term changes and MAU models for the more complex long term changes.

3.4.2 Chung & Chen (1989)

Experience at Toyota [see Masuyama (1983)], has shown that flexibility can be captured by two factors:

- quick response to a change, and
- economical response to a change.

Chung & Chen (1989) explore these two factors as follows:

- **Quick response to a change:** Quickness can be evaluated with respect to the lead time between customer's order receipt and the completion of products. Lead time consists of the following:

  * lead time of processing information, includes demand forecast, ordering,...,etc.
  * lead time of manufacturing, includes machining, subassembly, inspection,...,etc.
  * lead time of transportation, includes material handling and distributing final products.

  For a response to a change to be quick, the lead times need to be minimized.

- **Economical response to a change:** Quick response to a change alone is an inadequate criterion for evaluation. The system can be made capable of responding to a change very quick but at the expense of an enormous capital investment. For example, an FMS using a large number of versatile machine tools, sophisticated industrial robots and material handling systems might be capable of responding to a change very quickly. However, the extensive investment may not be economical. While judging economical response, factors like inventory level and machine utilizations should also be evaluated.

Chung & Chen (1989) attempt to measure the effect of flexibility on system performance considering quick and economical response factors as relevant performance measures to obtain a measure of flexibility. They suggest that quick and economic response to a change are two conflicting objectives. Usually there is a need either to maximize the customer service or to minimize the cost, or to optimize one of these objectives while keeping the other at a prescribed level. Thus, they suggest assigning a weight, α, to these objectives in order to obtain a measure of flexibility.

$$F = \alpha Q + (1 - \alpha)E$$

where

F is a measure of flexibility

Q is the quickness of response to a change

E is the economical response to a change

α is the importance weight assigned to Q , $0 < \alpha < 1$

In general Q and E represent the time and money spent to cope with a given change.

Following issues constitute a criticism of the above approach to measure flexibility:

1. Usually, there are several changes to be coped with and thus, there are several Q and E factors related to measure of flexibility, i.e. the curse of dimensionality remains.
2. Quickness of the response for a specified change depends on the timeframe in which change affects production . For example, quickness concept is different for a machine breakdown and a product innovation. That means, seven days spent to repair a machine may not be accepted as quick enough, while one year spent for a product innovation is acceptable. Roughly speaking, quickness of response factor of short term changes can be measured in minutes or hours while the same factor can be measured months and years for medium and long term changes respectively. As a result the importance of short term changes can be undermined. Thus, at least a rough categorization of changes is required which will further constitute short, medium and long term components of flexibility.
3. At the same time, the weight, α, can be different for different types of changes. For example quickness of the response can be more important than economical response for a machine breakdown. As the time spent to repair the broken machine increases, WIP may increase and inventory levels may decrease resulting n a major disruption of deliveries. In fact, machine breakdowns are usually referred as short term changes and there is a need to cope with short term changes in a short term timeframe. On the other hand, an economical response to product innovations can be more important than quick response. This is because, product innovations may require additional capital investments. Therefore, different weights should be assigned to different changes depending on:
   - processing times,

  - lead times,
  - inventory levels,
  - scheduling rules,
  - delivery reliability,
  - market share,
  - competitors,.., etc.

4. Economical response to a change factor also depends on the quickness of response factor because there is an opportunity cost associated with the time spent to respond. As an example, machine breakdowns may result in significant production losses, and thus an opportunity cost occurs associated with these production losses.

5. In equation (3.1), time and money spent are added in order to obtain the measure of flexibility. Unfortunately it is not possible to obtain a unit by adding hours and dollars.

However, above listed deficiencies can be overcome partially. That is,

* The set of changes to be coped with can be decomposed into three subsets i.e. ,

  set of short term changes,

  set of medium term changes and

  set of long term changes.

* To simplify the analysis, changes in these subsets can be classed such as demand changes, machine breakdowns etc., and importance weights for the same class can be assigned to be the same.

* An opportunity cost, associated with the time spent to cope with a change, can be assessed and can be used to convert the quickness of the response factor into monetary units.

* Relative frequencies (or probability distribution functions) of short, medium, and long term changes can be considered.

Such a scheme for flexibility measurement creates some difficulties associated with providing the input data (time spent, money spent, opportunity cost, statistical information). In order to obtain input data, the use of time consuming and expensive techniques like utility analysis, statistics or simulation are inevitable However, change-based understanding still motivates a future research on flexibility measurement.

Quick response to a change can be represented by minimized *manufacturing lead time* subject to the financial viability determined by top management level. Manufacturing lead time further consists of *setup time*, *processing time* and *waiting time*. Reduced setup, processing and waiting times and minimized opportunity costs associated with these can provide a motivation for flexibility investments. Furthermore, machine utilization level is another important factor in evaluating the viability of flexible equipment. Flexible equipment provides higher utilizations when product mix and the product portfolio change. Idle time gives information about machine utilization. Reduced idle time, (minimized opportunity cost associated with idle time), is another motivation to invest in flexible technology. Thus incorporating and minimizing opportunity costs may achieve changes in some performance measures which are indicative of increased flexibility.

3.4.3 Buzacott (1982)

Buzacott (1982) attempts to measure the effect of flexibility on productivity and efficiency (machine utilization). He considers two types of flexibility:

- job flexibility, and
- machine flexibility.

In order to illustrate the typical relationship between productivity and flexibility, he develops some simple models of manufacturing systems. The results of his study are interesting because these results are consistent with our discussion on minimizing the manufacturing lead time and optimizing the opportunity costs associated with the components of manufacturing lead time. Buzacott (1982) concludes that as flexibility increases:

1. a possible decline in productivity should be minimized,
2. increase in efficiency should be maximized.

According to his results,

1. Minimizing the decline in productivity requires:
   - 1.a. minimized setup times,
   - 1.b. minimized waiting times, and
   - 1.c. the appropriate layout of workstations to minimize material movement.
2. Maximizing the increase in efficiency requires:
   - 2.a. increased machine capabilities,
   - 2.b. an enlarged set of alternative routes, and
   - 2.c. work-in-process control.

However, Buzacott's approach does not consider any costs. Thus, it is desirable to include the proper cost information in an appropriate modelling approach so that the optimum degree of flexibility can be determined. These ideas are explored in the next two chapters.

3.5 Finding Realistic Performance Measures

In general there are two different ways of obtaining set P:

- type-based approach, and
- change-based approach.

Among these change based approach seems to be more promise to obtain more realistic performance measures. This is because type based approach focus mainly on physical properties of the system and ignores the importance of operating policies and managers' preferences. Several performance measures have been suggested according to type-based understanding, but they are far away being meaningful indicators of the system performance. Other limitations of type-based performance measures have been discussed in section 3.2.

However if capability ease approach is folllowed by a task force the performance measures obtained can better represent managers' preferences and the specifics of the system. Actually, capability-ease approach for understanding flexibility inherits a naive measurement scheme :

1. Specify the changes to be coped with.
2. Consider only one change.
3. Select the appropriate performance criterion.
3. Monitor the performance.
5. Decide whether or not a deterioration in performance takes place:
   - If so, justify the ease (time spent, money spent,..,e.t.c.) and give the penalty.
   - If not, give the credit.
6. Go to step 2, repeat until all changes are considered.

According to Mandelbaum (1978) any evaluation of flexibility must consider the effectiveness of the system in coping with each change, as measured by the loss or benefit, if the change took place. Same idea is represented by capability-ease approach more explicitly. Buzacott (1982) states that with a manufacturing system the loss associated with a change has three components:

* **Infeasibility:** The change may be such that the system is unable to operate (e.g. it can not process parts of a particular type because it has not the capability to do so).

* **Productivity:** The rate of production is reduced or the use of limited resources is increased.

* **Quality:** The quality of parts produced is impaired.

While explaining capability-ease approach, we considered the loss associated with a change as having not only three, but many components. In capability-ease approach this loss is measured by the deterioration of performance where the components and acceptable level of this loss is decided by the managers or the task force. The infeasibility issue explained above is captured by capability-ease approach. The managers or the task force conclude that the loss associated with a change is more than a specified amount (i.e. if the system is not capable to cope with a change because of a very high penalty cost). Thus capability-ease approach provides valuable insight to management about how flexibility effects the system performance when performance is measured by the many different factors (like work-in-process, productivity, quality, production loss,..., e.t.c.) that experience has shown to be relevant. Thus capability-ease approach provides a naive framework for both understanding flexibility and obtaining realistic performance measures indicative of flexibility.

Chapter 4

Justifying Flexibility Investments

4.1 Justification Barrier

In general, flexibility investments include equipment based, automation alternatives. Meredith and Suresh (1986) conceive that, manufacturing equipment has historically been justified on the basis of,

- cost reduction and
- capacity expansion.

So that, flexibility investments are typically expected to be justified on the same basis. Usually, obtaining *economies of scale* is one of the primary goals of the firms. This is why investments are made in capacity expansion and cost reduction. *Economies of scale means increasing the volume of production in order to decrease unit costs.* On the other hand, greater volumes may require the use of expensive special purpose equipment which in turn is justified only by large scale operations. If demand happens to be low, expected cost reductions from capacity expansion will fail. Goldhar and Jelinek (1983) introduce the concept of *economies of scope* which mainly relies on flexibility. Increasing the variety of products that can be produced is a requirement for demand uncertainty. Moreover, a rapidly changing market demand will result in an economic order quantities approaching one. Flexibility provides rapid responses to changes in market demand, product design, product mix and output rates. Therefore, *economies of scope* i.e. *efficiencies gained by increasing the variety of products and decreasing the volume of production*, is one of the driving forces to invest in flexible technology.

Articles citing the inadequacy of traditional engineering economic procedures to justify flexibility investments are abundant [see Kaplan (1986), Choobineh (1986), Meredith & Suresh (1986), Canada (1986), Falkner (1986.b), Park & Son (1988), Suresh (1990.b)]. The realization that traditional engineering economic procedures are barriers to invest in flexibility is only a symptom of a basic problem evaluating all the true costs and benefits associated with this technology. This problem is compounded, due to the fact that many of the advantages of flexible technology lie not in the area of cost reduction, but rather in more nebulous and *strategic* areas such as shorter lead times, increased quality and competitiveness. The benefits of flexible technology come from *tactical*, *operational* and *strategic* sources. Benefits coming from strategic sources are not easily quantified. This has been referred to as the *quantification dilemma*. In addition to the quantification dilemma, flexible technology requires a high initial investment which results in a high degree of risk. Consequently, notwithstanding the many desirable benefits, flexibility investments have been difficult to justify.

Several major problems have been identified associated with the use of traditional engineering economic procedures [see Falkner (1986.b), Suresh (1990.a), Suresh (1990.b), Falkner & Benhajla (1990)]. The criticism pertaining to these procedures revolves around the following issues:

a. **Myopic Approach:**
Quick and tangible returns are emphasized rather than long term strategy because of short term oriented reward systems.

b. **Treatment of Intangibles:**
The range of benefits considered is diminished because of the difficulties in quantifying the improvements in intangible factors.

c. **Quantification Dilemma:**
While it is accepted that flexibility investments provide many desirable benefits, a strategically important flexibility alternative can easily be rejected only because it does not satisfy a particular financial criteria. In many cases managers are expected to consider strategic factors without quantification.

d. **Uncertainty Assumptions:**
A variety of assumptions are made to forecast the demand and cash flows due to the fact that it is difficult to deal with future uncertainty.

Suresh (1990.b) reports that the justification problems can also be traced to several factors unique to the flexible technology itself, i.e. ;

a. the high capital costs and risk associated with this technology;

b. the high rates of obsolescence, prompting a *'wait and see'* response;

c. the differing nature of operations, which are now part family oriented, and;

d. the combinatorial complexity due to many types of flexibility which has led to difficulties in economic evaluation.

Besides the criticism of the use of traditional engineering economic procedures, some of the experts agree that financial analysis is sufficient and the use of financial criteria is appropriate; unless these are not considered in the wrong way.

According to Primrose & Leonard (1986), flexibility investments only make economic sense if all costs and benefits can be included in an evaluation. They also claim that all the benefits which were regarded as intangible can be redefined in a way that they could be quantified and included in an evaluation. Thus, discounted cash flow (DCF) techniques can be utilized. At the same time, Kaplan (1986) emphasizes that, managers need not abandon the effort to justify flexibility investments on financial grounds and instead, they need to apply the DCF approach more appropriately. In many instances DCF approach is applied incorrectly by setting excessively high hurdle rates to provide a protection from risk. Because, it is believed that taking high-risk should provide a high probability for high-return. However, ***high-return projects*** may mean innovative projects which may result in increased market competitiveness, rather than projects with a high internal rate of return (IRR) or net present value (NPV). Really, Kaplan puts the blame on the management by saying that, it is not the model's responsibility but management's to judge whether the negative NPV is outweighted by the anticipated nonquantified benefits.

In particular, Falkner & Benhajla (1990) point out the fact that, justification process is usually carried out independent of the management and instead, the information about financial viability is delivered in the form of summarized tables of cash flows and financial measures. Considering only the financial measures the 'gap between costs and unquantifiable benefits ' can easily outweigh anticipated nonquantified benefits. As a result, although it is clear that managers must pursue innovation and flexibility in a rapidly changing manufacturing environment; it is also evident that expensive, long term and risky flexibility investments can easily fail economic justification, under these conditions.

Hodder (1986) surveys justification techniques that are used in Japan and makes a comparison to the techniques used in U.S.A. His results are interesting. Even though most of the Japanese manufacturers use financial criteria based on DCF techniques, they have a greater willingness to undertake long term risky projects. The reason seems to be that; along with the financial analysis they usually employ an extensive discussion process, which might be termed as *verbal scenario analysis*, involving a number of managers from different areas and levels of the firm. Consequently, potential investments receive full discussion even if their IRR or NPV is relatively poor. This seems to avoid the problem of rejecting strategically important projects just because they did not satisfy the particular financial criterion. Considering Japanese managers' attitudes, we conclude that management function in financial evaluation can be improved by more active participation.

Certainly, there is a need to modify the data available for economic analysis as well as to provide active management participation for justifying flexibility investments [Park & Son (1988), Primrose & Leonard (1984), Parkinson & Avlonitis (1982), Kaplan (1986)].

In particular, traditional cost accounting procedures are not designed to provide information directly relative to the benefits of the new technology. That is, these procedures are designed to report financial status rather than to assist management in making decisions to improve operational efficiency. Thus, there is also a need to deal with cost accounting problems.

In summary, during the current development of justification procedures the problems to be dealt with are the following:

1. Conceptual limitations of traditional techniques to consider all aspects of flexibility.
2. Accounting problems in order to asses all true costs and benefits of flexible technology.
3. Providing active management participation within the firms.

4.2 Creating a Sound Basis for Justification

Required modifications to justification procedures should be made depending on the situation, the industry and the manufacturing strategy of the firm. A task force which consists of system engineers and managers can be formed in order to provide active organizational participation. In fact, a task force should be constructed to play an important role as a committee of experts during installation and implementation as well as during justification. Thus, continuous performance improvement through organizational learning and experimentation can be achieved as Jaikumar (1986) argues. The problem of providing basic frameworks on understanding and justifying flexibility, that the task force can follow, can be approached theoretically.

In recent years there have been significant development in the theory of justification of flexibility investments. Based on a MAU model, Falkner & Benhajla (1990) propose a new justification process which incorporates performance evaluation into the economic justification process. Suresh (1990.a) presents a decision support system (DSS) as a basis to consider both physical performance measures and financial criteria by means of simulation. Park & Son (1988) suggest a reclassification of manufacturing costs which can better motivate flexibility investments. The theoretically different approaches of Falkner & Benhajla (1990) , Suresh (1990.a) and Park & Son (1988) are all valuable contributions in terms of creating a sound basis for justifying flexibility investments [see also Pollard & Tapscott (1989)]. A detailed review of these studies can be found in the following subsections.

4.2.1 A New Justification Process

Falkner & Benhajla (1990) conceive that the historical justification process can be viewed as shown in figure [4.1]. That is, usually the information about the completed justification is delivered to the management, and then a choice is made in the management decision process. The choice may be selecting a one of the mutually exclusive alternative manufacturing systems to invest and implement, or it may be a yes-no answer about the investment and implementation decision. If the justification results in a decision for addition of a relatively small production system, once the new system is installed, it becomes a microcosm in the factory accounting system. The factory accounting system generally is not designed to provide information needed auditing the system effectiveness. If the justification process results in an implementation decision of a new plant, then accounting system reports the profitability to provide a natural feedback. Falkner & Benhajla (1990) state that, unfortunately, this feedback system is used only from operational control viewpoint and is rarely used to evaluate the justification process. They also point out the fact that, while there is not a formal feedback on the justification process in order to improve it, there is certainly an informal one which determines the level of optimism and conservatism of the management relative to investments.

In view of the above observations, Falkner & Benhajla (1990) propose a new justification process illustrated in figure [4.2]. This process utilizes the formalism of a MAU model as a means of combining the traditional methodologies with the other significant factors experience has shown to be relevant. Therefore, the significant factors and information which the management decision function must consider are highlighted and, a framework

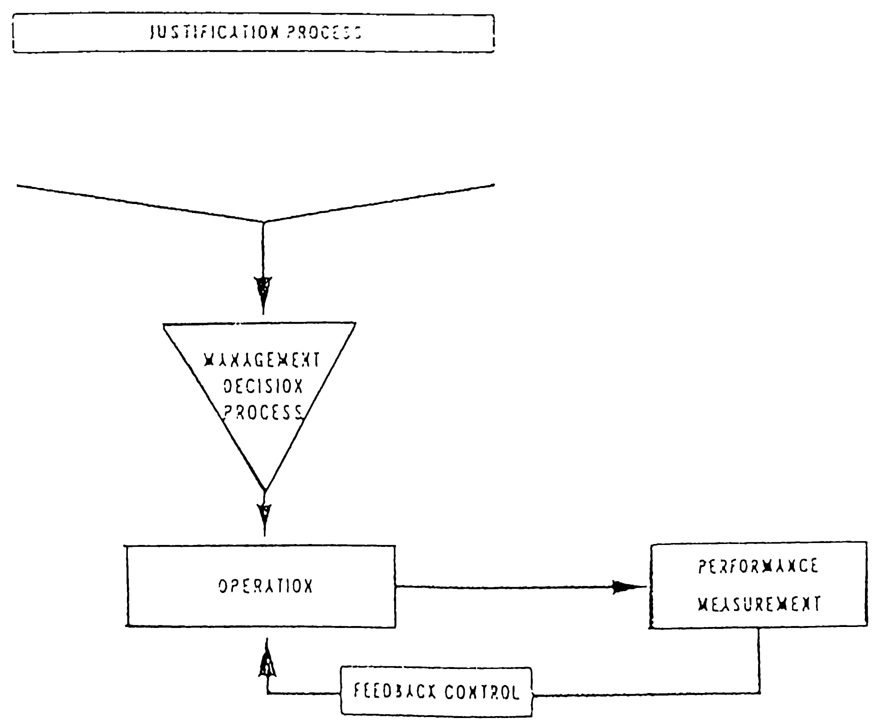


Figure 4.1: Current Justification Process: Falkner & Benhajla (1990)

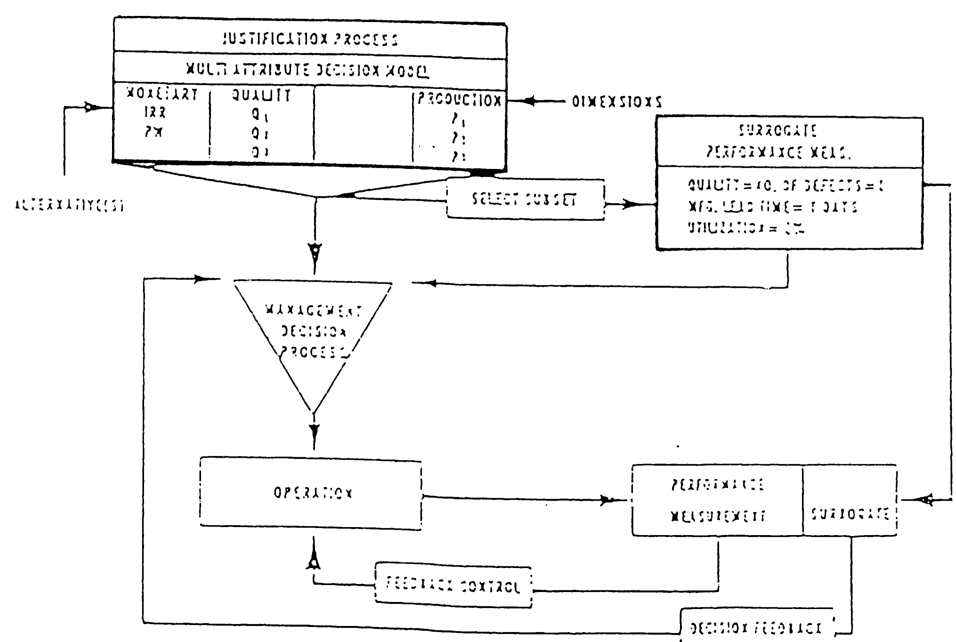


Figure 4.2: Proposed Justification Process: Falkner & Benhajla (1990)

for more active management participation is provided.

In a model based on MAU theory, a subset of additional attributes are included. These attributes are specified to be non-monetary factory performance measures which will constitute an integral part of the operational control system and are called surrogate performance measures. It is suggested that these surrogate performance measures provide the basis for a formal feedback mechanism on the justification. Actually, the proposed justification process shows how economic justification and performance evaluation can be integrated and how such an integration can improve the justification process.

4.2.2 A DSS Structure

Burstein (1988) suggests the use of a mixed integer mathematical programming model to generate formal decision rules can be used to analyze hypotheses about the optimal introduction of flexible and (or) dedicated automation. Fine & Freund (1990) develop a general mathematical programming model of the cost-flexibility tradeoffs involved in investing in product flexible manufacturing capacity. Azzone & Bertele (1989) outline a method for the evaluation of FMS alternatives considering future product mix changes as well as other strategic and economic aspects. Boer & Meltzer (1986) present a simulation approach for economic analysis of an FMS in a planning context.

Suresh (1990.a) states that as the base of analytical and simulation models continues to grow, there is a need to integrate the diverse range of tools and techniques into an effective decision support system (DSS). Suresh (1990.a) develops such a DSS structure by explicitly considering the need for structuring wide ranging input data and the need for synthesizing a variety of analytical, simulation and rule-of-thumb methods. The proposed decision process is illustrated in figure [4.3]. A simulation model is embedded in this DSS structure. Machine,product and volume flexibility are integrated into the configuration data while expansion,routing and process flexibility are included within the operating policies. An integrated physical-financial evaluation is recommended, arguing that an integrated evaluation enables a simultaneous financial evaluation of system

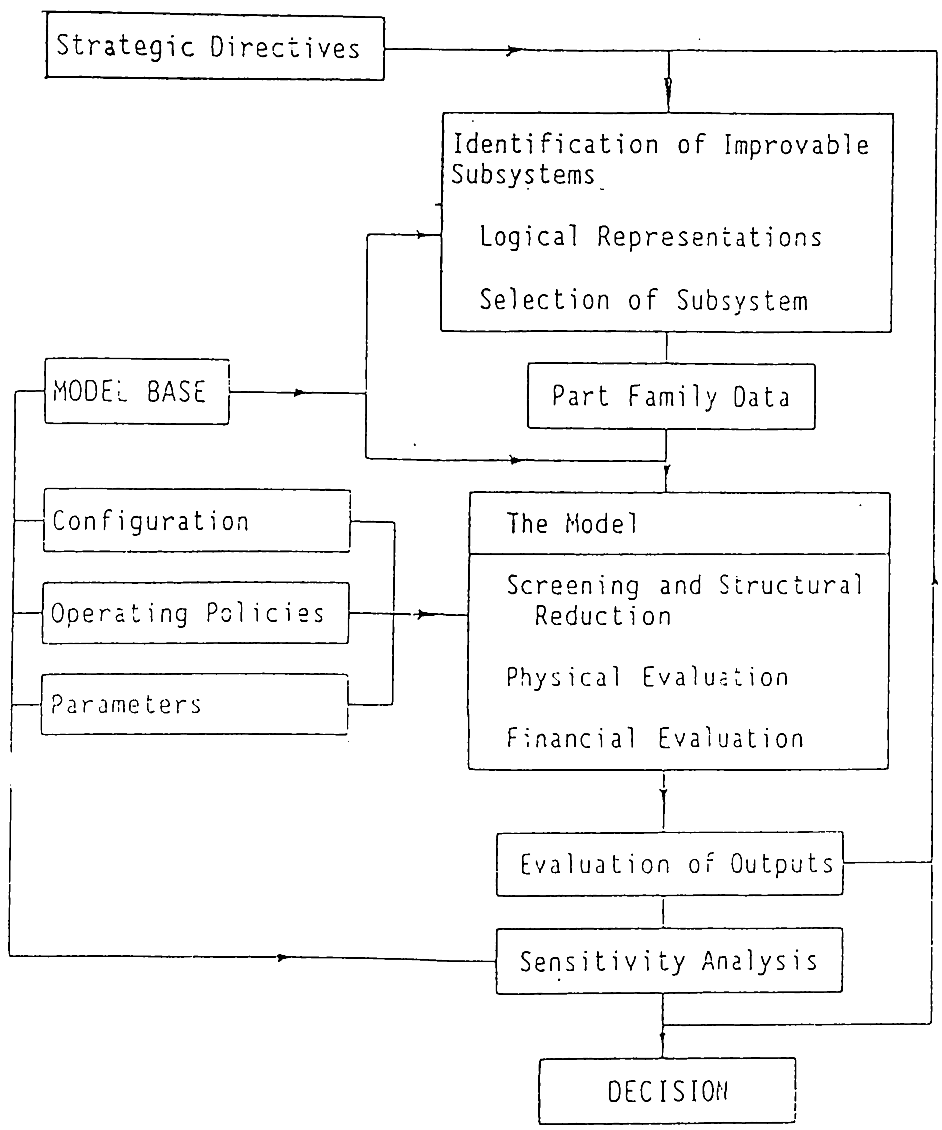


Figure 4.3: Proposed Decision Process: Suresh (1990.a)

changes, physical system design and operating policies. In fact, Suresh's study provides a useful framework to facilitate integrated physical financial evaluation.

4.2.3 A Reclassification of Costs

Most authors agree that the final investment decision should be made on a basis of financial considerations in order to avoid financial liability. Azzone & Bertele (1989) argue that this is true even a strategic approach is followed; the only way to define the most suitable manufacturing system for the firm's long term position is the most profitable system. Since there is a need to take into account financial considerations, the substantial benefits of flexibility investments should be reported by an appropriate cost accounting system.

Park & Son (1988) point out that with traditional methods of cost accounting, these flexibility benefits go undetected because current accounting measures are based on the production of a mature product with known characteristics and a stable technology. They argue that, in introducing flexible technology, improvements in productivity, quality and flexibility should be considered.

Figure [4.4] illustrates the conventional income and expense classification. After concluding that such a cost accounting system is not designed to report economic benefits from a more flexible system, the reclassification of costs shown in figure [4.5] is suggested by Park & Son (1988). This cost classification is used in a mathematical programming model which is formulated to maximize the NPV of an optimal multistage investment decision. A discussion on this model formulation can be found in the following sections.

4.2.4 Analytical Models on Economic Evaluation of Flexibility Investments

Throughout the remaining part of this chapter we give a review of the literature on analytical models of flexibility investment justification and evaluation. Fine (1990) also

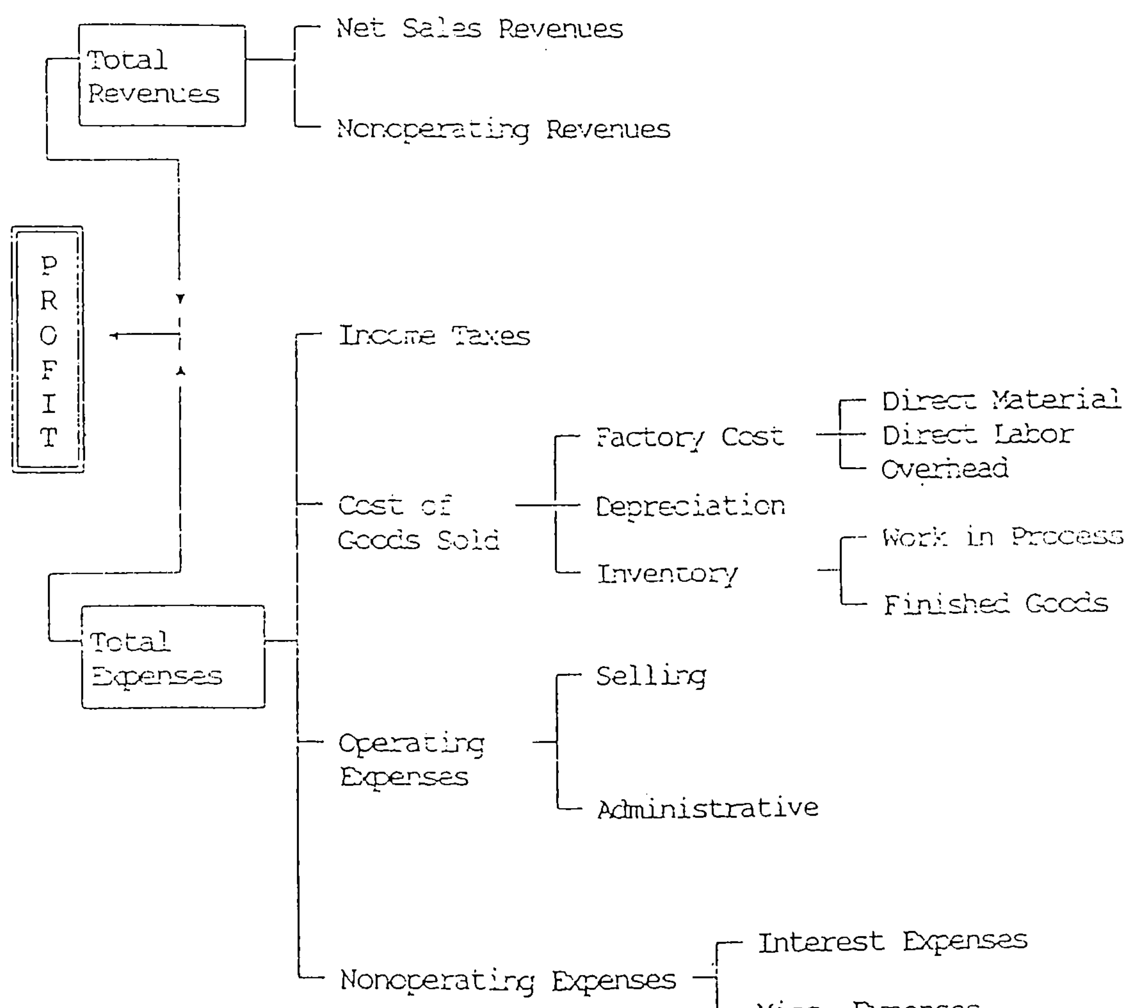


Figure 4.4: Conventional Classification: Park & Son (1988)

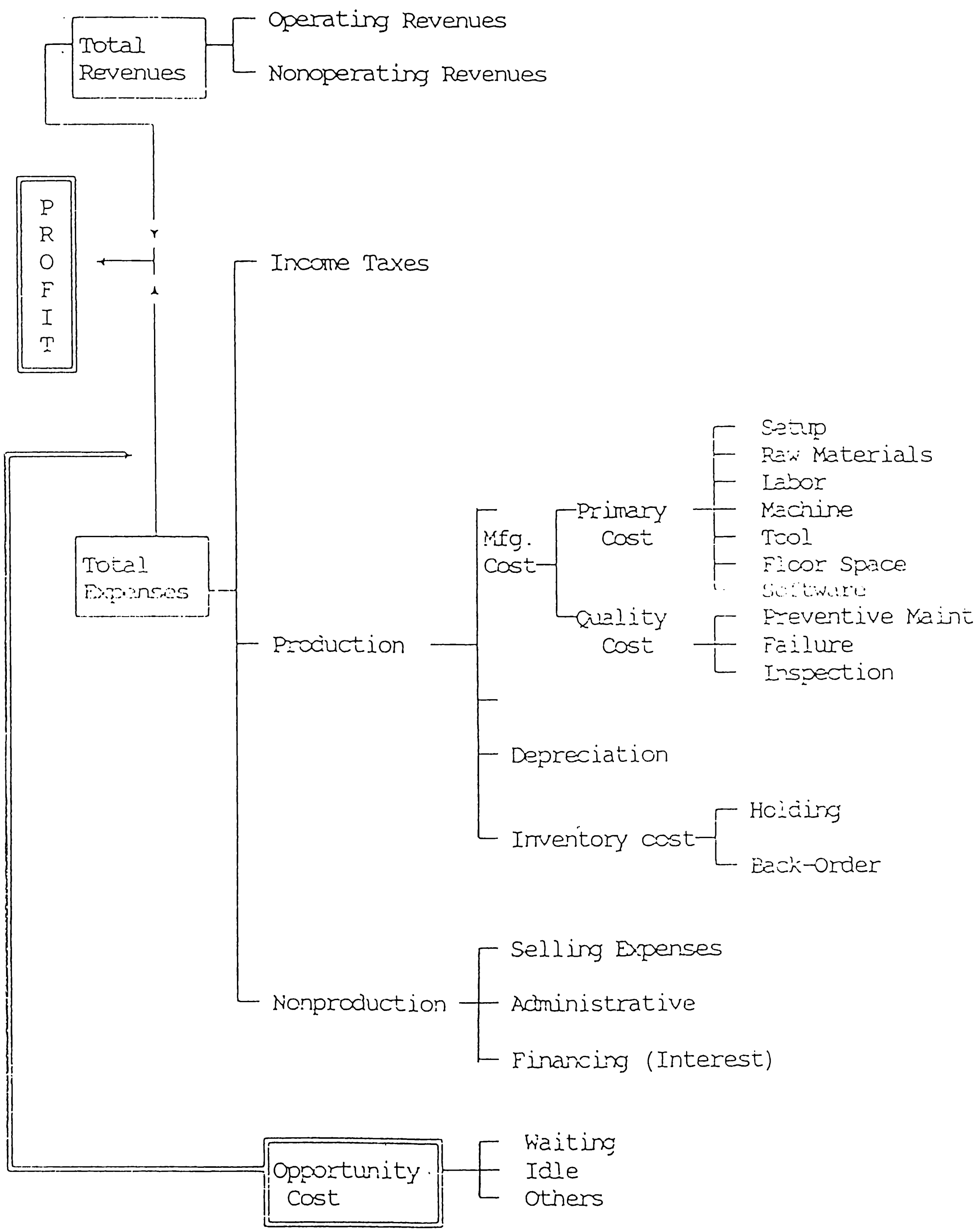


Figure 4.5: Proposed Classification: Park & Son (1988)

discusses several lines of research on economic evaluation models for new technology and a review of the recent literature on analytical models can be found in Verter & Dinçer (1991). In general normative models on the evaluation and justification of flexible technology fall into four groups:

1. Simulation models,
2. Multiattribute decision models (**M**ultiattribute **U**tility (**MAU**) theory and **A**nalytic **H**ierarchy **P**rocess (**AHP**)),
3. **M**ulti **O**bjective **D**ecision (**MOD**) models, and
4. **M**athematical **P**rogramming (**MP**) models.

The limitation of simulation approaches [see Boer & Meltzer (1986), Falkner & Garlid (1986), Suresh (1990.a)] is that they are not as good at optimization as they are at comparing a fixed set of alternatives.

MAU and AHP models are favored [see Canada (1986), Falkner (1986.b), Varney et.al. (1985)] due to the multidimensional nature of flexibility and quantification dilemma. Falkner & Benhajla (1990) provide a detailed survey of the literature on multiattribute decision models. These models provide methods for choosing from a fixed set of alternatives.

MOD models are suggested in order to deal with the multiple objectives while investing in flexible technology. Furthermore some of the well known advantages of both MP and MAU theory modelling approaches can be utilized by MOD models. Stam & Kuula (1989) and Kuula & Stam (1989) employ a multiple criteria analysis for FMS selection decisions. Suresh (1990.b and 1990.c) suggests a goal programming formulation as a multi objective replacement model for flexible automation investments. Suresh & Kaparthi (1990) further investigates an economic evaluation methodology for replacement decisions, based on a synthesis of goal programming and AHP approaches.

In the following subsections, we restrict our discussion to three MP modelling approaches to economic evaluation and justification of flexibility investments:

- a technology selection model by Fine & Freund (1990),
- an evaluation model by Park & Son (1988), and
- a multimachine replacement model by Suresh (1989).

In general we focus on the flexibility considerations within the models and do not discuss the computational complexities and solution methodologies.

4.2.5 Fine & Freund Model (1990)

Fine and Freund (1990) developed a two-stage stochastic quadratic programming model to analyze the choice between dedicated and flexible technologies under uncertainty. This model formalizes the capacity investment problem and can be used to determine the optimal mix of flexible and dedicated capacity. The focus of their analysis is the use of flexible technology as a hedge against uncertainty in future demand. In fact, Fine & Freund (1990) provide an integrated a capacity acquisition and technology selection model.

FLEXIBILITY CONSIDERATIONS:

The only flexibility consideration is the unit acquisition cost of flexible technology. Other cost elements are assumed to be technology independent, because in most cases material costs dominate other cost items since the products to be produced are specified. Demand of the products are taken into account as random variables and consequently product flexibility is captured partially.

THE MODEL:

Capacity decisions in the first stage constrain the production amounts in the second stage where the product markets may be in different states with discrete probabilities. Optimal technology mix is selected via maximizing the expected profit. Fine and Freund (1990) implicitly assumed a monopolist firm by presuming that it will be possible to sell the quantity which maximizes the expected profit. The authors derived the necessary and sufficient conditions for purchasing flexible capacity from the model.

Fine and Freund (1990) assumed that capacity acquisition and variable production costs are linear and the latter are technology independent. Further, downward-sloping linear demand curves are assumed which makes the revenue functions quadratic. The problem is nontrivial only if the flexible technology is cheaper than the sum of all dedicated technologies but more expensive than each of them. By the aid of a two-product example it is demonstrated that perfect negative correlation between product demands is the situation in which the flexible technology is most preferable.

4.2.6 Park & Son Model (1988)

In general, justification process involves the question of whether or not the incremental cash flows from investment justify the required the capital outlay. Park & Son (1988) state that another relevant question is, whether or not there is any opportunity cost associated with not adopting new technology e.g. a cost of not having flexibility. In their analysis an **opportunity cost** is defined as *the potential after tax profit that is lost or sacrificed when the choice of one course of action requires giving up an alternative course of action.* The idea is that although opportunity costs do not represent actual dollar outlays, they do represent the economic benefits that are foregone. Thus, they are relevant to the investment decision. Moreover, opportunity costs associated with not having flexibility may provide a motivation to invest in flexible technology. Therefore, the incremental cash flows resulting from a decrease in opportunity costs should be considered when evaluating investment in flexibility.

Park & Son (1988) formulate a multiperiod investment decision linear programming model to evaluate alternative investment projects [see also Son & Park (1987), Son & Park (1990)]. The less obvious benefits of flexible technology are incorporated into a convensional net present value function measuring manufacturing performance over a specified planning horizon. The model can be used to decide whether or not to modify the current manufacturing system or to choose from new manufacturing system alternatives.

FLEXIBILITY CONSIDERATIONS:

Park & Son view flexibility as ' a degree of manufacturing performance that indicates a system's adaptability to changes in the manufacturing environment '.

It is argued that, since customer demand is an uncontrollable variable benefits from adding flexibility do not always increase sales. That is, cost of adding flexibility may not be by justified economies of scale. In case where production is reduced to match decreasing demand, the company should benefit from lower costs. In brief, Park & Son explicitly assume that the main advantage of flexibility is the capability of the system to accommodate the changes in market demand by economical and quick responses. They suggest that manufacturing flexibility can be described by four costs indicated in figure [4.5]:

- setup cost,
- waiting cost,
- idle cost, and
- inventory cost.

In fact, these costs are introduced to be measures of four different flexibility types. The following flexibility types are defined and considered:

1. **Equipment flexibility**, is defined as the capacity of equipment to accommodate new products and variants of existing products and measured in terms of idle cost.

Idle cost is an opportunity cost associated with the under-utilization of manufacturing equipment. Thus, if idle cost is reduced, the machines will be utilized better despite the frequent introduction of new products and variants of existing products. Minimized idle cost implies that idle time is minimized and current equipment is being used effectively in response to changing market demand.

2. **Product flexibility** represents opportunity of the system to increase the value of products due to the changes in product mix. Since the changes in product mix result in smaller lot sizes as variety increases, higher setup costs are inevitable. Setup cost is suggested to be a measure of product flexibility. The idea is that reduced setup time permits shorter production runs and reduced machine idle time. Thus it is argued that setup cost is an opportunity cost because during the setup procedure the machine is idle and parts are waiting.

3. **Process flexibility** is defined as the adaptability to changes in part processing and measured by waiting cost. Part processing changes can be caused by machine setup and breakdowns. When the system is not able to respond these changes quickly WIP increases proportional to waiting time and cost. Waiting cost is the opportunity cost associated with parts that are waiting for service in the manufacturing process. Thus waiting time and cost should be minimized to reduce the capital tied up in WIP.

4. **Demand flexibility** is defined as adaptability of the system to changes in demand rate and measured by inventory cost. If an effective action can be taken to meet increasing and decreasing demand the inventory costs disappear. An opportunity cost accompanies inventory cost due to capital tied up in inventory.

THE MODEL :

The model explicitly considers idle, setup, waiting and inventory costs along with traditional investment costs. A reduction in these costs can help to motivate an invest in flexible technology rather than some other alternative technology. Son & Park (1990) discuss how idle, setup, waiting and inventory costs can be estimated by means of simulation. In fact these opportunity costs are viewed as the investments required to retain a project rather than the alternative project. Given the input data (e.g. initial investment, cost factors, annual budgets) an optimal annual budget allocation for the resources and annual production quantities for the products can be obtained over the planning horizon. An hypothetical numerical example is also presented to demonstrate the application this model.

Model Formulation

$$\text{Maximize NPV} = \sum_{n=0}^{N}[-F_n + S_n + tDP_n]r_n$$

$$+\sum_{n=1}^{N}\sum_{i=1}^{I}[(1-t)[P_{in}(X_{in}+I_{i,n-1}-I_{in})-(C_{in}^{T}X_{in}+h_{in}I_{in}+b_{in}B_{in})]-w_{in}X_{in}]r_n \quad (1)$$

subject to

$$\sum_{i=1}^{I} c_{in}^{k}X_{in} \leq M_n^k \qquad k=1,..,11,\ n=1,..,N, \quad (2)$$

$$\sum_{i=1}^{I}(h_{in}I_{in}+b_{in}B_{in}) \leq M_n^{12} \qquad n=1,..,N, \quad (3)$$

$$\sum_{k=1}^{12} M_n^k \leq M_n^T \qquad n=1,..,N \quad (4)$$

$$X_{in}+(I_{i,n-1}-B_{i,n-1})-(I_{in}-B_{in}) = D_{in} \qquad i=1,..,I \quad n=1,..,N \quad (5)$$

$$X_{in}\geq 0,\quad I_{in}\geq 0,\quad B_{in}\geq 0 \qquad i=1,..,I \quad n=1,..,N \quad (6)$$

(7)

where,

$n \in N$ = set of time periods in the planning horizon (N = project life),

$i \in I$ = set of part types to be produced,

t = marginal tax rate,

r_n = discounting factor $(1/(1+k)^n)$,

F_n = investment at period n,

S_n = net salvage value at period n,

DP_n = depreciation at period n,

P_{in} = unit selling price for product i at period n,

X_{in} = production amount (lot size) for product i at period n,

D_{in} = demand of product i at period n

I_{in} = inventory level for product i at period n,

B_{in} = back-order level for product i at period n,

C_{in}^{T} = unit manufacturing cost for product i at period n,

c_{in}^{k} = resource k required to make a unit product i in period n , where $k = 1, ..., 11$ denotes setup cost, raw-material cost, labor cost, machining cost, tooling cost, floor-space cost, software cost, prevention cost, failure cost, waiting cost, idle cost respectively.

h_{in} = unit inventory holding cost of product i at period n,

b_{in} = unit back-order cost of product i at period n,

$w_{in} = c_{in}^{10} + c_{in}^{11}$ = unit opportunity cost for product i at period n,

M_{n}^{k} = individual budget of resource k at period n,

M_{n}^{12} = individual budget of inventory holding and back-order at period n,

M_{n}^{T} = total budget at period n.

4.2.7 Suresh Model (1989)

Suresh (1989) develops a multiperiod replacement model for incremental implementation of flexible automation investments. For many investment justification problems, flexible technology can be adopted in a phased approach. Suresh (1989) emphasizes that with a phased implementation several benefits may be foregone and opportunity costs may be incurred by prolonging the installation phase. However, it may offer some financial and operational advantages such as lower capital outlays, better absorption of the new technology into the firm, experience for future installations, and a more manageable production environment during the transition period. He also addresses the critical issue that there is a need for multiperiod models which take into account characteristics of flexible technology. The main assumption of Suresh's study is the use of flexible technology is conceptually validated with in the firm and therefore the objective is to find the optimal replacement sequence of machines dependent on possible future scenarios. Suresh (1989) pays special attention to the dependence of the optimal replacement policy on currently available capacity and future demand,prices and costs. This is an important contribution because in many instances firms do not start from scratch. In fact the solution to the model can be a mix of flexible and dedicated capacities. Thus, the proposed replacement model can also be viewed as an integrated technology selection and capacity acquisition model.

FLEXIBILITY CONSIDERATIONS:

Suresh (1989) considers five flexibility types as defined by Browne et.al. (1984):

1. **Expansion flexibility:** The incremental implementation approach takes expansion flexibility explicitly into account as a major factor. Expansion is assumed to be feasible and its economic value is represented by the optimal NPV.

2. **Volume flexibility** is explored is explored by comparing the optimal NPV for various scenarios of production volumes.

3. **Routing flexibility:** Routing flexibility can be obtained by allowing redundancy in a machine group as well as versatility in other groups. Since versatility in a machine group is captured by machine flexibility, a capacity slack factor γ is introduced to investigate routing flexibility.

4. **Machine flexibility:** Versatility of the machines are represented by the binary valued parameters denoting processing capabilities. In addition the corresponding setup time and cost are used to explore machine flexibility.

5. **Product flexibility:** Suresh (1989) assumes that part family with strategic payoffs has been identified. The objective of the replacement is to meet the estimated future demand and make the production profitably. Part types considered may or may not be produced with current machines. The set of part types may also include some

which are expected to be introduced later in the planning horizon. Thus product flexibility can be partially investigated according to different part family scenarios.

THE MODEL:

The proposed model is based on a mixed integer linear programming formulation which maximizes NPV resulting from investment decisions and manufacturing operations over a specified planning horizon. The decision variables are the replacement sequence of current machines, the implementation sequence of new modules, and aggregate production plans based on optimum machine assignments. The constraints include demand requirements, capacity limitations , operational capability limitations and implementation requirements. It is assumed that newly installed machines are not replaced during the planning horizon. By the aid of a numerical example, it is illustrated how flexibility types can be investigated via NPV as a performance measure.

Model Formulation:

$$\text{Maximize NPV} = \sum_{n=1}^{N}\sum_{i=1}^{I}(P_{in} - c_{in}^{2})D_{in}(1-t)r_n$$

$$+\sum_{n=1}^{N}\sum_{m_2=1}^{M_2}(y_{m_2,n} - y_{m_2,n-1})F_{m_2,n}(1 - IC_{m_2,n})r_n + \sum_{n=1}^{N}\sum_{m_1=1}^{M1}(y_{m_1,n-1} - y_{m_1,n})S_{m_1,n}r_n$$

$$+\sum_{n=1}^{N}[\sum_{m_2=1}^{M_2} DP_{m_2,n} + \sum_{m_1=1}^{M_1} DP_{m_1,n}]tr_n$$

$$-\sum_{n=1}^{N}[(\sum_{i=1}^{I}\sum_{j=1}^{J_i}\sum_{m_2=1}^{M_2}\delta_{i,j,m_2}X_{i,j,m_2,n}) + (\sum_{i=1}^{I}\sum_{j=1}^{J_i}\sum_{m_1=1}^{M_1}\delta_{i,j,m_1}X_{i,j,m_1,n})](1-t)r_n$$

$$-\sum_{n=1}^{N}[(\sum_{i=1}^{I}\sum_{j=1}^{J_i}\sum_{m_2=1}^{M_2}\epsilon_{i,j,m_2}y_{m_2,n}) + (\sum_{i=1}^{I}\sum_{j=1}^{J_i}\sum_{m_1=1}^{M_1}\epsilon_{i,j,m_1}y_{m_1,n})](1-t)r_n$$

$$-\sum_{n=1}^{N}[(\sum_{i=1}^{I}\sum_{j=1}^{J_i}\sum_{m_2=1}^{M_2}c_{i,j,m_2}^{1}(X_{i,j,m_2,n}/L_{i,n}))+(\sum_{i=1}^{I}\sum_{j=1}^{J_i}\sum_{m_1=1}^{M_1}c_{i,j,m_1}^{1}(X_{i,j,m_1,n}/L_{i,n}))](1-t)r_n$$

$$-\sum_{n=1}^{N}\sum_{i=1}^{I}(L_{i,n}/2)h_{i,n}r_n + BV_N r_N \qquad (8)$$

subject to

$$y_{m_1,n} \leq y_{m_1,n-1} \qquad \forall m_1 \ , \ n \quad (9)$$

$$y_{m_2,n} \geq y_{m_2,n-1} \qquad \forall m_2 \ , \ n \quad (10)$$

$$y_{m_1,n} = 0 \qquad \forall n = l_{m_1} \quad (11)$$

$$DP_{m_2,n} = DP_{m_2,n-1} + (y_{m_2,n} - y_{m_2,n-1})F_{m_2,n}d_{m_2} \qquad \forall m_2 \ , \ n \quad (12)$$

$$DP_{m_1,n} = DP_{m_1,n-1} + (y_{m_1,n} - y_{m_1,n-1})F_{m_1,n}d_{m_1} \qquad \forall m_1 \ , \ n \quad (13)$$

$$X_{i,j,m_2,n} \leq z_{i,j,m_2} D_{i,n} \qquad \forall i \ , \ j \ , \ m_2 \ , (14)$$

$$X_{i,j,m_1,n} \leq z_{i,j,m_1} D_{i,n} \qquad \forall i \ , \ j \ , \ m_1 \ , (15)$$

$$\sum_{m_2=1}^{M_2} X_{i,j,m_2,n} + \sum_{m_1=1}^{M_1} X_{i,j,m_1,n} = D_{i,n} \qquad \forall i \ , \ j \ , \ n \ (16)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J_i} t_{i,j,m_2} X_{i,j,m_2,n} + \sum_{i=1}^{I}\sum_{j=1}^{J_i} A_{i,j,m_2}(X_{i,j,m_2,n}/L_{i,n}) \leq \gamma y_{m_2,n} K_{m_2,n} \qquad \forall m_2 \ , \ n (17)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J_i} t_{i,j,m_1} X_{i,j,m_1,n} + \sum_{i=1}^{I}\sum_{j=1}^{J_i} A_{i,j,m_1}(X_{i,j,m_1,n}/L_{i,n}) \leq \gamma y_{m_1,n} K_{m_1,n} \qquad \forall m_1 \ , \ n (18)$$

$$BV_N - \sum_{n=1}^{N}\sum_{m_2=1}^{M_2} (y_{m_2,n} - y_{m_2,n-1})F_{m_2,n}(1 - IC_{m_2,n}) + \sum_{n=1}^{N}\sum_{m_2=1}^{M_2} DP_{m_2,n} = 0 \qquad (19)$$

where,

$n \in N$ = set of time periods in the planning horizon (N = project life),

$i \in I$ = set of part types to be produced,

$j \in J_i$ = set of operations for part type i,

$m_1 \in M_1$ = set of current machine types (set of modules having more than one machine of the same type) to be replaced, item[] $m_2 \in M_2$ = set of new machine types (set of modules having more than one machine of the same type),

t = marginal tax rate,

r_n = discounting factor $(1/(1+k)^n)$,

$y_{m_1,n}, y_{m_2,n}$ = number of units of machine type m_1 and m_2 operating in time n,

$F_{m_1,n}$ = capital cost of machine type m_1 at the time of installation,

$F_{m_2,n}$ = capital cost of machine type m_2 at the time of installation,

$IC_{m_2,n}$ = investment credit factor for machine type m_2 in time n,

$S_{m_1,n}$ = salvage value of machine m_1 if replaced in time n,

$DP_{m_1,n}, DP_{m_2,n}$ = depreciation computed for machine types m_1 and m_2 for period n,

d_{m_1}, d_{m_2} = straight line depreciation factors for machine types m_1 and m_2,

BV_N = book-value of the assets at the end of the planning horizon,

z_{i,j,m_1}, z_{i,j,m_2} = equals 1 if operation j of part type i can be performed in type m_1 and m_2 respectively; 0 otherwise,

t_{i,j,m_1}, t_{i,j,m_2} = processing times for operation j of part type i in machine types m_1 and m_2 respectively,

A_{i,j,m_1}, A_{i,j,m_2} = preparation times per lot for operation j of part type i in machine types m_1 and m_2 respectively,

$\delta_{i,j,m_1}, \delta_{i,j,m_2}$ = variable cost per unit for operation j of part type i in machine types m_1 and m_2 respectively,

$\epsilon_{i,j,m_1}, \epsilon_{i,j,m_2}$ = fixed cost per unit for operation j of part type i in machine types m_1 and m_2 respectively,

$c^1_{i,j,m_1}, c^1_{i,j,m_2}$ = setup cost for operation j of part type i in machine types m_1 and m_2 respectively,

$c^2_{i,n}, c^2_{i,n}$ = material cost per unit for part type i in period n,

$h_{i,n}, h_{i,n}$ = inventory holding cost per unit for part type i in period n,

$P_{i,n}$ = price of part type i in period n,

$X_{i,j,m_1,n}, X_{i,j,m_2,n}$ = production quantities for operation j of part type i in time n in machine types m_1 and m_2 respectively,

$L_{i,n}$ = lot size for part type i in time n,

$D_{i,n}$ = demand forecast for part type i in time n.

4.3 Comparison

A number of different approaches and models have been suggested for economic evaluation of flexibility investments. Among these basically we have chosen to concentrate on two MP models:

1. Park & Son (1988): Park & Son models a particular investment alternative to obtain NPV as a measure of its manufacturing performance. Thus to select from say three alternatives one must exercise the model for each and then choose the one resulting in the greatest NPV. This model can be used prior to one-time implementation of a complete system.

2. Suresh (1989): Suresh develops a multiperiod replacement model for an incremental implementation of flexible automation investments. He combines the selection of alternatives into the model. Park & Son assume the selected alternative is to be implemented now, whereas Suresh allows the selected equipment to be time phased in implementation over the planning horizon.

In their model Park & Son assume one lot for each period. On the other hand Suresh allows many lots, and the lot size can be a decision variable. However if the lot size becomes a decision variable, then Suresh's model turns out to be a nonlinear mixed integer program. This certainly increases the computational complexity. Generally in FMS-like systems several lots per period are expected due to smaller sizes. Thus Suresh's lot size consideration seems to be more relevant.

Park & Son gives a penalty to idle cost. This implies their model minimizes idle time. Nevertheless minimized idle time usually results in overscheduling. Overscheduling should be avoided for flexibility. Because additional loads are imposed on alternate machines, for example in case of a machine breakdown, and there is a need for planned underutilization of equipment to take this into account. Thus Suresh considers a capacity slack factor γ to allow excess capacity for flexibility and avoidance of overscheduling.

Park & Son aim at making the budget allocation as well as deciding the production amount for each period. Therefore they express the resources in dollars and their capacity constraints are imposed by the total budget available. Because they use a reclassification of costs, the major areas to which the firm's resources are committed include items like prevention, failure, waiting, idle, and inventory. With these factors the LP model reflects some important aspects to invest in flexible technology.

On the other hand, Suresh aims at determining the optimal replacement sequence and the aggregate production plans based on optimal machine assignments during the planning horizon. The capacity constraints are imposed by total time available and the operational capabilities of the equipment. Suresh uses the conventional classification of costs. However the reclassification of costs considered by Park & Son seems to be more relevant, because it allows less obvious benefits of flexible technology to be incorporated into the objective function.

Park & Son allows holding inventory from one period to the next whereas Suresh restricts the production to meeting the demand. Suresh includes in-process inventory holding cost, but Park & Son do not. In process inventory holding cost should be considered however, if one large lot is produced in a period.

Finally note that flexibility benefits incorporated into the models differ. This is due to the differences in conceptual considerations in the models. Park & Son consider a reclassification of costs in order to incorporate financial advantages of flexible technology in their model. In machine replacement context, Suresh basically considers the technological advantages of flexible technology and does not convert these into monetary terms. The differences in terminology associated with flexibility types are caused by the lack of consensus on flexibility type definitions in 1980's.

4.4 How to Improve Incremental Implementation Models

Suresh's model includes a fairly gross incremental implementation assumption. The formulation requires that a module consists of an entire flexible manufacturing cell or FMS and perhaps a FAS. This is due to the fact that each new module is considered to be independent of the other new modules. One very reasonable sequential implementation plan is the incremental implementation of an FMS itself. Suppose the conceptual design of an FMS involves k different types of NC machines. Then the first sequential implementation would involve some combination of a single machine of each type so that the tooling and part programs can be proved. The existing material handling system and manual loading/unloading would be used. The next implementations might be any replicate machines, automated handling system, and the computer controls. However the addition of the last two items does not add additional capability but modifies the capability previously implemented, i.e. it changes ease measurements such as setup time and cost and processing time. One method of modeling this situation might be to allow some new modules to replace new modules and add precedence constraints to control which new modules can be replaced and the replacement timing.

In the next Chapter we formulate a multimachine replacement model which improves upon Suresh (1989). We do not attempt to overcome the above problem. Rather we consider modules which consists of single machines and provide refinements in flexibility considerations.

Chapter 5

Manufacturing Flexibility in the Justification of Advanced Automation Investments

5.1 Incremental Implementation of Flexible Technology

The investment justification problems associated with the one-time installation of flexible technology have been addressed in Chapter 4. Over the last few years incremental implementation of flexible technology have been suggested as a remedy for these problems, because it leads to lower annual capital outlays. Furthermore incremental implementation is more relevant than one-time installation in many cases since usually firms do not start from scratch. Suresh & Sarkis (1989) report that a majority of firms are believed to be adopting an evolutionary strategy of implementing flexible technology. According to them the poor linkage between corporate and manufacturing strategies have contributed to the slow adoption rates in case of a one-time installation. Actually, several U.S. firms were not able to achieve the performance targets due to the lack of experience in managing flexible systems. In many instances failure in performance is accompanied by a failure in attaining expected strategic payoffs [Jaikumar (1986), Boer et.al. (1990)]. Incremental implementation may provide a more effective transition and absorption of flexible technology permitting increased learning and experimentation within the firms. Therefore the problem of incremental implementation and integration of flexible technology is being addressed formally in recent years.

Suresh (1989) reports that with an incremental implementation several benefits may be foregone and opportunity costs incurred by prolonging the installation phase, but it may also offer some financial and operational advantages which can not be ignored:

- it leads to lower capital outlays in each period,
- operationally, it offers a slower, and perhaps a more effective transition and absorption of advanced technology within the firm,
- it may lead to a more manageable production environment in the transition period,
- it provides a hedge against several factors of uncertainty:
  - later investments may be made in the light of the experience with earlier investments,
  - a partial resolution of uncertainty surrounding the demand and obsolescence in process/product technologies can be gained.
- subsystems installed earlier may help pay for modules to be implemented later,
- initially implementing subsystems which provide tangible benefits, in a bottleneck area for instance, may serve to reduce internal resistance and justification problems.

As presented in Chapter 4 Suresh (1989) developed a multimachine replacement model for flexible automation investments which incorporates these advantages. A review of the historic perspective of equipment replacement studies can be found in Suresh (1989) and Suresh (1990.b). According to Suresh (1989) there is a need for multiperiod replacement models that address the following issues relevant to flexible automation investments:

- The models should provide a framework for incremental implementation, with the one-time installation of an integrated system forming a special case.

- The models should provide a rational basis for the monetary evaluation of hedging against uncertainities.
- The models should take into account the several dimensions of flexibility of CNC-based systems.

In this chapter a mixed-zero-one nonlinear programming, multimachine, multiperiod replacement model is developed for incremental implementation of flexible automation investments. The model formulation is similar to Suresh (1989). Our suggestion is different from the earlier studies in a way that a new cost system suggested by Son (1991) is used and further refinements are provided in flexibility considerations. In the following sections we discuss the problem definition, flexibility considerations, and model formulation of our model consequently.

5.2 A Cost Estimation Model By Son (1991)

In Chapter 4 we have addressed that there is a need to deal with accounting problems in order to assess all true costs and benefits of flexible technology. In general, it is currently realized that existing cost measures should be updated for reliable decision making about advanced manufacturing. Therefore, Son (1991) defines cost elements which should be included in the analysis of advanced manufacturing systems. Briefly, he defines costs of productivity, quality and flexibility and their components [see Figure (5.1)]. He groups these three costs into two categories of *Relatively Well-Structured Costs* (RWSC) and *Relatively Ill-Structured Costs* (RISC) . Productivity cost elements are RWSC because they are actual tangible input items required to make a product, which have been understood by accountants for decades. On the other hand, quality and flexibility costs are RISC because there is no commonly accepted way of calculating these. Son (1991) divides the conventional manufacturing cost into direct labor, direct material and overhead. Overhead is broken into many categories for accurate evaluation of changes due to factory automation. He also proposes a quantitative method of estimating the cost elements indicated in Figure (5.1) and presents various approaches to collecting parametric input data of the cost model.

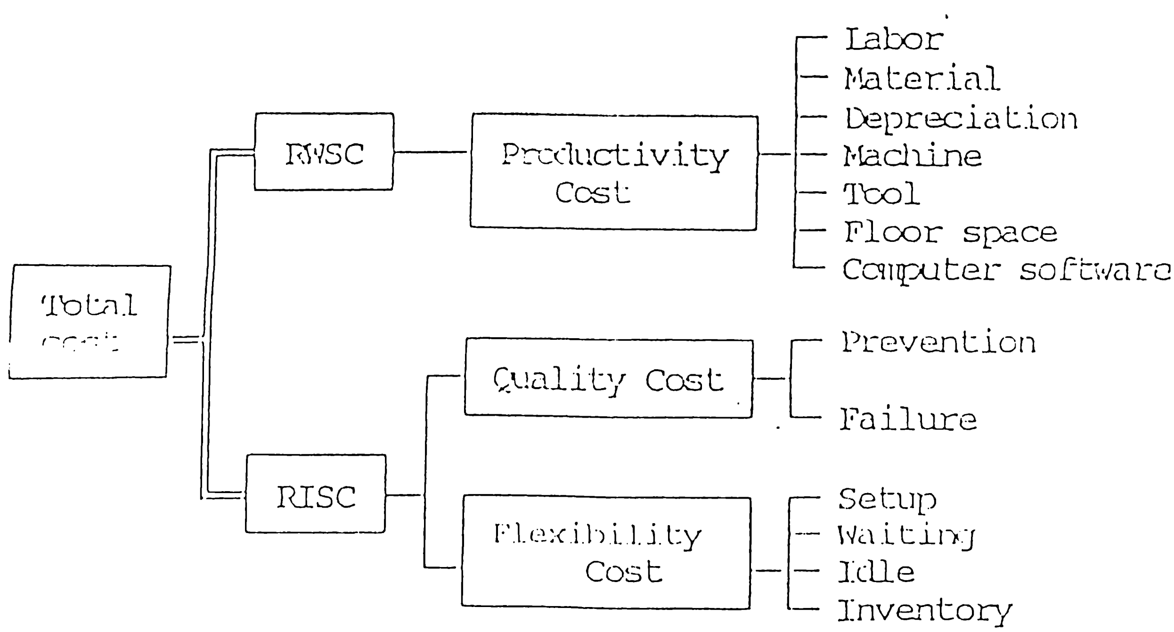


Figure 5.1: A cost system supporting analysis of advanced manufacturing systems: Son (1991)

The rational for using such a cost classification and the model formulation of Park & Son (1988) have been discussed in Chapter 4, Section 4.2.5. In our model we use the cost classification indicated in Figure (5.1), but omit quality cost items and add in-process inventory holding cost to include several additional aspects of flexibility.

5.3 Problem Context and Definition

Suresh (1990.c) states that the complexities of flexible automation systems generally require the design and evaluation to be carried out in two phases: first, a high-level approximation phase, followed by detailed design and evaluation [see Figure (5.2)]. The purpose of the approximation phase is to narrow down the configuration choices. Given the numerous choices in part family, configuration, parameters and operating policies the number of candidate systems tends to explode. Therefore analytical approximations are required prior to detailed design and evaluation.

Our model is intended for use as an analytical approximation. It is designed to serve as a decision support tool which is a component of the DSS model as described in Suresh (1990.a) and summarized in Chapter 4. However for our model, there is a need to integrate the cost estimation model provided by Son (1991) into the DSS model suggested by Suresh (1990.a). The notation is introduced under the categories of part family data [PF], configuration data [CF], accounting considerations [AC], operating policies [OP], and parameters [PR].

NOTATION

- Part Family Data [PF] :

  $i \in I$ = set of part types to be produced,

  $j \in J_i$ = set of operations for part type i,

  $\Omega = \bigcup_{i=1}^{I} J_i$; set of all operations required,

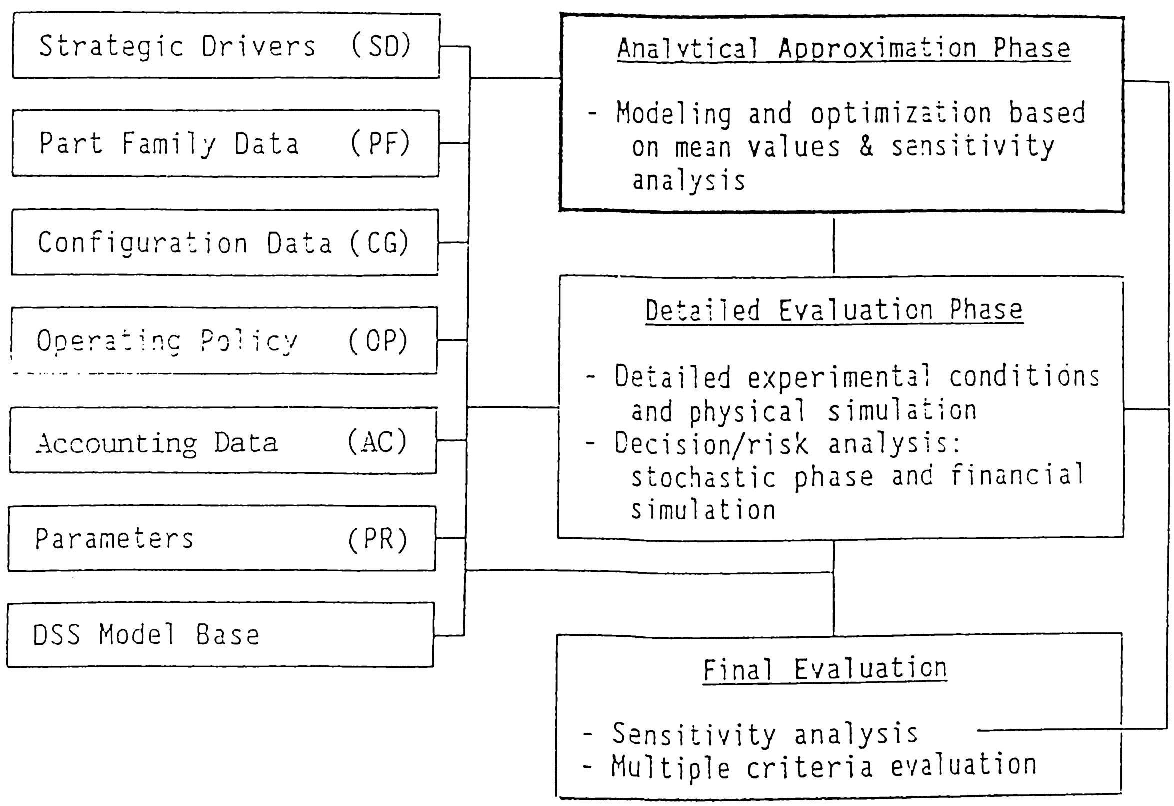


Figure 5.2: Problem Context

$\Psi \subset \Omega$ = set of operations which are unique i.e. require the same machine capability,

$D_{i,n}$ = demand forecast for part type i in time n,

- Configuration Data [CF] :

$a \in A$ = set of current machine types to be replaced,

$b \in B$ = set of new machine types,

K_a, K_b = capacity of machines a and b respectively (in hours),

$w_{i,j,a}, w_{i,j,b}$ = equals 1 if operation j of part type i can be performed in type a and b respectively; 0 otherwise,

$t_{i,j,a}, t_{i,j,b}$ = processing times for operation j of part type i in machine types a and b respectively,

$SU_{i,j,a}, SU_{i,j,b}$ = setup times per lot for operation j of part type i in machine types a and b respectively,

l_a = period after which the life time of machine type a ends,

- Accounting Considerations [AC] :

F_a = capital cost of machine type a at the time of installation,

$F_{b,n}$ = capital cost of machine type b at the time n,

$S_{a,n}$ = salvage value of machine a if replaced in time n,

$DP_{a,n}, DP_{b,n}$ = depreciation computed for machine types a and b for period n,

d_a, d_b = straight line depreciation factors for machine types a and b,

$P_{i,n}$ = price of part type i in period n,

$C_{i,n}$ = material cost per unit for part type i in period n,

$\delta_{i,j,a,n}, \delta_{i,j,b}$ = variable cost (labor, tooling, e.t.c.) per unit of operation j of part type i on machine types a and b respectively in period n,

$\epsilon_{i,j,a,n}, \epsilon_{i,j,b,n}$ = fixed cost (floor space, computer software, e.t.c.) per unit of operation j of part type i on machine types a and b respectively in period n,

$\epsilon_{a,n}, \epsilon_{b,n}$ = avarage fixed cost of machines a and b respectively in period n,

$\alpha_{i,j,a,n}, \alpha_{i,j,b,n}$ = setup cost for operation j of part type i in machine types a and b respectively, in period n,

$\beta_{i,j,n}$ = unit waiting cost of operation j of part type i in period n,

γ_a = idle cost per unit time for machine a,

γ_b = idle cost per unit time for machine b,

$h_{i,n}$ = inventory holding cost per unit for part type i in period n,

$v_{i,n}$ = in process inventory holding cost per unit for part type i in period n,

BV_N = book value of the assets at the end of the planning horizon,

- Operating Policies [OP] :

$Y_{a,n}$ = 1 if machine type a is operational in period n, otherwise 0,

$Z_{b,n}$ = 1 if machine type b is operational in period n, otherwise 0,

$X_{i,j,a,n}, X_{i,j,b,n}$ = production quantities for operation j of part type i in time n in machine types a and b respectively,

$L_{i,n}$ = lot size for part type i in time n,

$I_{i,n}$ = inventory of part type i in time n.

$IT_{a,n}, IT_{b,n}$ = idle time of machines a and b respectively in period n

φ = capacity slack factor $0 \leq \varphi \leq 1$,

- Parameters [PR] :

$n \in N$ = set of time periods in the planning horizon (N = project life),

t = marginal tax rate,

r_n = discounting factor $(1/(1+k)^n)$,

k = minimum attractive rate of return.

It is assumed that a candidate part family which will be manufactured in the flexible automation system has been identified. The part types are denoted by the index set $i \in I$. For a given part type $i \in I$, the operations to be performed are denoted by the set $j \in J_i$. At present these operations are performed using the current machine types, or manufacturing processes, denoted by the index set $a \in A$. Current machines $a \in A$ are earmarked to be progressively replaced by new, CNC machines, or modules denoted by the index set $b \in B$. New machines $b \in B$ are to be selected, progressively integrated and evaluated over planning horizon $n \in N$. The binary variable $Y_{a,n}$ assumes a value of one if current machine $a \in A$ is operated in period n, and a value zero after it is phased out. Similarly, the binary variable $Z_{b,n}$ assumes a value zero if the new machine b is not installed in period n, and a value one after it is purchased.

The operation capabilities of the current machines $a \in A$ and new machines $b \in B$ are represented by incidence matrix elements $w_{i,j,a}$ and $w_{i,j,b}$ respectively which assume a value of one if operation j of part type i (i.e. operation (i,j)) can be processed on the corresponding machine, and zero otherwise. The number of incidence matrix elements, $w_{.,.,b}$ equal to one is expected to be greater than number of elements $w_{.,.,a}$ equal to one since $b \in B$ are flexible machines. Furthermore if $w_{i,j,a} = 1$ then $\sum_b w_{i,j,b} \geq 1$ i.e. the set of new machines must have at least one machine that can perform (i,j). For each operation (i,j) setup and operation times are denoted by $SU_{i,j,a}$, $t_{i,j,a}$, $SU_{i,j,b}$, $t_{i,j,b}$ for machines $a \in A$ and $b \in B$ respectively. Similarly the setup costs $\alpha_{i,j,a}$ and $\alpha_{i,j,b}$, fixed costs $\epsilon_{i,j,a}$ and $\epsilon_{i,j,b}$, variable costs $\delta_{i,j,a}$ and $\delta_{i,j,b}$ of operation (i,j) on machines $a \in A$ and $b \in B$ respectively are specified for each operation capability. At the same time the idle costs $\gamma_{a,n}$ and $\gamma_{b,n}$ associated with idle time at machines $a \in A$ and $b \in B$ respectively in period n are considered. The unit waiting cost $\beta_{i,j,n}$ associated with each operation (i,j) performed in period n is taken into account.

The current machines are salvaged during the transition period, and the estimated salvage value ($S_{a,n}$) contributes to the cash flow. The capital costs for new modules ($F_{b,n}$), demand ($D_{i,n}$), price ($P_{i,n}$) and material costs ($C_{i,n}$) need to be estimated for each period.

During the transition period parts may be produced using both current and new machines. The assignment of operations and production quantities is based on the operation capabilities of the available machines and the optimal, economic utilization of flexibility.

The operation sequence is assumed to be not important for each $i \in I$. Production quantities are denoted by the decision variables $X_{i,j,a,n}$ and $X_{i,j,b,n}$ indicating the assignment of operation (i,j) to machines $a \in A$ and $b \in B$ respectively in period n.

The objectives of the model are to determine the optimal replacement sequence (decision variables $Y_{a,n}$ and $Z_{b,n}$), and the optimal assignment of production quantities (decision variables $X_{i,j,a,n}$ and $X_{i,j,b,n}$). The objective function consists of the net present value of manufacturing operations including the investment expenses. Investment in flexible automation can be motivated by net savings from reduced setup, idle, waiting, and inventory costs considered in the objective function. Actually these cost items are identified as opportunity costs associated with not having flexibility.

In brief a part family and its manufacturing processes are modelled as a whole in contrast to machine-level equipment replacement problem. Specific aspects and advantages of flexibility like reduced setup costs and higher utilization are taken into account in order to justify the investment in flexible automation. A detailed discussion on opportunity costs of not having flexibility and how these are treated in the model is provided in the next section.

5.4 Modeling Flexibility

Modeling the economic impact of flexibility is a basic requirement for the evaluation of flexible automation. Because investment in flexible technology make economic sense only if all true costs and benefits can be incorporated in the evaluation model. Therefore the capability-ease notion associated with flexibility has been adopted as discussed in Chapter 2.

'*Manufacturing systems are designed under conditions of incomplete and uncertain knowledge. The process of designing a manufacturing system begins by defining the strategic derivers, including flexibility goals and developing a conceptual design* ' [Carter (1986) p:107] We assume that the use of flexible automation is validated conceptually during predesign depending on the flexibility goals. In fact our model is aimed at determining the optimal replacement sequence by new flexible machines i.e. designing flexibility into the system in the most economical way. In the machine replacement context designing flexibility implies introducing new processing capabilities. These new processing capabilities may allow the system to cope with changes at a certain degree of ease. In general flexibility studied by the model solution is based on technological specifications. However by postoptimality analysis and obtaining solutions under different scenarios the flexibility of the complete system can be investigated.

In our model existing elemental capability (i.e. operation capabilities of machines) is represented by a binary-valued parameter. The ease for a particular operation is measured by setup time and cost, fixed cost, variable cost, idle time, processing time and indirectly by lot size. Solving the model results in selecting the best capabilities considering ease tradeoffs i.e. an optimal design of flexibility. As an example of postoptimality analysis, since the solution is determined by the demand one would need to find the demand space over which the replacement sequence remains optimal. Sensitivity of the resulting NPV to demand changes shows capability and ease of the system to demand accomodate these changes. This also provides an indication of product and volume flexibilities.

The investment decision for new machines represents introducing a capability. All the current machines are allowed to be phased out if they need not to be operated for an optimal solution. If current machines are replaced by new machines machine flexibility is increased. However, replacement depends on whether or not the incremental net cash flows from replacement justify the added investment. That means introducing capability with a certain degree of ease requires a capital outlay which needs to be justified. Therefore introducing a capability should translate into economic benefits like increasing the cash flows or leading the strategic benefits like improved lead time. At the same time, current machines need not to be replaced if their useful life is more than the planning horizon. If they are not replaced the sum of real and and opportunity costs associated with retaining the current machines is less than the sum of real and opportunity costs associated with implementing a new machine.

' *Opportunity costs do not represent actual dollar outlays. Rather they represent those economic benefits that are foregone as a result of pursuing some alternative course of action, and thus they are relevant to investment decisions.* ' [Park & Son (1988) p:7]. In a multimachine replacement decision, our model is aimed at comparing the current machines with the alternative new machines. Therefore in our model four opportunity cost items are considered:

- setup,
- waiting,
- idle,
- inventory.

Thus the net savings from opportunity costs by introducing a capability (i.e. buying a new machine) can be viewed as economic benefits of flexible automation which are translated into cash flows.

Generally, there is a cost associated with designing flexibility in a manufacturing system which increase the initial cost of the system and needs to be justified. Moreover there is a cost associated with not having flexibility. This is the opportunity cost associated with production lost, time spent, increased lead time etc. while coping with changes, in order to survive. Cost of not having flexibility is usually an opportunity cost as illustrated in figure[2.4]. Investment in flexible automation may result in net savings from these cost items and this would motivate to invest in flexible automation.

5.5 The Model

As mentioned before, the decision variables in the model include the configuration related binary variables ($Y_{a,n}$ and $Z_{b,n}$) which gives the replacement sequence and the production assignments ($X_{i,j,a,n}$ and $X_{i,j,b,n}$) and the lot sizes ($L_{i,n}$). The constraints and the objective function are below.

5.5.1 Constraints

(1.) Hard Implementation Constraints:

Following two constraint sets ensure that current machines current machines are to be phased out and the new machines are installed:

$$Y_{a,n} \leq Y_{a,n-1} \quad \forall a \, , \, n$$

$$Z_{b,n} \geq Z_{b,n-1} \quad \forall b \, , \, n$$

It is assumed that:

- the disposal of a current machine occurs at the beginning of of a period,
- the new modules are to be implemented at the beginning of a period, and
- the new modules cannot to be replaced during the planning horizon.

The current machines may have to be phased out by a specified time period, i.e. at the end of their useful time. This is ensured by the following constraint set:

$$Y_{a,n} = 0 \quad \forall n = l_a \leq N$$

(2.) Computing Depreciation:

Depreciation values are computed by the following two constraint sets using the straight-line method:

$$DP_{a,n} = DP_{a,n-1} + (Y_{a,n} - Y_{a,n-1})F_a d_a \quad \forall a \, , \, n$$

$$DP_{b,n} = DP_{b,n-1} + (Z_{b,n} - Z_{b,n-1})F_{b,n} d_b \quad \forall b \, , \, n$$

At the beginning of the planning horizon depriciation value of machine $a \in A$ is $F_a d_a$, and it remains constant until a is phased out, and becomes 0 after a is disposed. Similarly at the beginning of the planning horizon depriciation value of machine $b \in B$ is 0, and it becomes constant $F_{b,n} d_b$ when $(Z_{b,n} - Z_{b,n-1}) = 1$ i.e. when b is installed.

(3.) Inventory Balance Equations:

Next we consider inventory balance equations. Year-end inventory is taken into account. For a given product $i \in I$ total production quantity $X_{i,n}$ in period n plus net inventory between periods $(n-1)$ and n is set equal to demand $D_{i,n}$:

$$X_{in} + I_{i,n-1} - I_{in} = D_{in} \quad \forall i\ ,n$$

(4.) Total Production Quantity of Operations:

Each operation $j \in J_i$ can be assigned to both current and new machines. Thus during the planning horizon total production quantity of operations $j \in J_i$ is split into quantity to be processed using current machines; $\sum_{a=1}^{A} X_{i,j,a,n}$, and quantity to be processed on new machines $\sum_{b=1}^{B} X_{i,j,b,n}$. For all $i \in I$ it is assumed that all $j \in J_i$ will be performed only once. Total production quantity of $j \in J_i$ is set equal to total production quantity of product i for all n.

$$\sum_{a=1}^{A} X_{i,j,a,n} + \sum_{b=1}^{B} X_{i,j,b,n} = X_{i,n} \quad \forall i\ ,\ j\ ,\ n$$

(5.) Production Assignments on Machines:

The production quantities $X_{i,j,a,n}$ and $X_{i,j,b,n}$ for an operation $i \in J_i$ in period n can be assigned to machines a and b respectively only if the machines are capable of performing the operation and operating in period n:

$$X_{i,j,a,n} \leq Y_{a,n} w_{i,j,a} X_{i,n} \quad \forall i\ ,\ j\ ,\ a\ ,\ n$$

$$X_{i,j,b,n} \leq Z_{b,n} w_{i,j,b} X_{i,n} \quad \forall i\ ,\ j\ ,\ b\ ,\ n$$

However these two constraint sets are nonlinear. Thus they are reformulated as:

$$X_{i,j,a,n} \leq w_{i,j,a} X_{i,n} \quad \forall i \ , \ j \ , \ a \ , \ n$$

$$X_{i,j,b,n} \leq w_{i,j,b} X_{i,n} \quad \forall i \ , \ j \ , \ b \ , \ n$$

If a machine is not operating in a given period then production assignment on that machine is forced to be zero by the **capacity constraints** discussed below.

(6.) Capacity Constraints:

The capacity constraints take into account the processing and setup times for each machine. Furthermore, capacity constraints ensure that if a machine $a \in A$ or $b \in B$ is not operational in a given period n production assignments are not made:

$$\sum_{i=1}^{I} \sum_{j=1}^{J_i} t_{i,j,a} X_{i,j,a,n} + \sum_{i=1}^{I} \sum_{j=1}^{J_i} SU_{i,j,a}(X_{i,j,a,n}/L_{i,n}) + IT_{a,n} = Y_{a,n} \varphi K_a \quad \forall a \ , \ n$$

$$\sum_{i=1}^{I} \sum_{j=1}^{J_i} t_{i,j,b} X_{i,j,b,n} + \sum_{i=1}^{I} \sum_{j=1}^{J_i} SU_{i,j,b}(X_{i,j,b,n}/L_{i,n}) + IT_{b,n} = Z_{b,n} \varphi K_b \quad \forall b \ , \ n$$

$IT_{a,n}$ and $IT_{b,n}$ is the idle time (capacity slack) of machines $a \in A$ and $b \in B$ respectively during the planning horizon. Idle time associated with not being able to process required operations having or unplanned underutilization of a machine is penalized in the objective function. The factor φ has been used to introduce a capacity slack in order to avoid overscheduling the system. This factor can be different for different machines. Actually the factor φ allows increased routing flexibility which is explained later. To keep the formulation linear, the lot sizes $L_{i,n}$ can be assumed to be parameters, decided on the basis of management policy. If they are allowed to be a decision variables as is desirable then these constraints are nonlinear. By letting:

$$X_{.,.,.,n}/L_{.,n} = lot_{.,.,.,n}$$

where $lot_{.,.,.,n}$ denotes the number of lots per period, and adding constraints these will be linear and nonlinear constraints are more easily handled using lagrange multipliers.

(7.) Redundant Operation Capabilities:

Increased operation capability within the system allows more than one routing for a given job and this ability can be utilized in response to machine breakdowns. Thus if the same operation capability is required more than one part following constraint ensures that redundancy in that operation capability is obtained at the end of the planning horizon:

$$\sum_{a=1}^{A} Y_{a,N} w_{i,j,a} + \sum_{b=1}^{B} Z_{b,N} w_{i,j,b} \geq 2 \quad \forall j \in \psi$$

(8.) Computing the Book Value of Assets at the end of The Planning Horizon:

The book value of assets at the end of the planning horizon is computed for inclusion in the objective function:

$$BV_N = \sum_{n=1}^{N}\sum_{b=1}^{B}(Z_{b,n} - Z_{b,n-1})F_{b,n} - \sum_{n=1}^{N}\sum_{b=1}^{B} DP_{b,n} + \sum_{a=1}^{A} Y_{a,N} S_{a,N}$$

5.5.2 The Objective Function

The objective function involves maximizing the net present value of the after tax cash flows over the planning horizon of N years. Less obvious benefits of flexible automation is incorporated into the conventional NPV index so that the long-term manufacturing performance can be measured.

First net present value of after tax cash flow from revenues of products sold, less material costs and the year-end inventory holding costs is expressed as:

$$\text{Maximize NPV} = \sum_{n=1}^{N}\sum_{i=1}^{I}[P_{in}(X_{in} + I_{i,n-1} - I_{in}) - (C_{in}X_{in} + h_{in}I_{in})](1-t)r_n$$

From this we subtract the outflows due to in-period inventory holding costs, operating costs, waiting costs, idle costs, and capital expenses.

Lot sizes should be decision variables. However as mentioned before, if it is necessary to keep the formulation linear they can be set as parameters. Then assuming an average inventory of $L_{i,n}/2$ for part i work-in-process holding costs is given by:

$$-\sum_{n=1}^{N}\sum_{i=1}^{I}(L_{i,n}/2)v_{i,n}r_n$$

Variable cost includes labor, machine, and tool costs. Variable costs are calculated as follows:

$$-\sum_{n=1}^{N}[(\sum_{i=1}^{I}\sum_{j=1}^{J_i}\sum_{a=1}^{A}\delta_{i,j,a}X_{i,j,a,n}) + (\sum_{i=1}^{I}\sum_{j=1}^{J_i}\sum_{b=1}^{B}\delta_{i,j,b}X_{i,j,b,n})](1-t)r_n$$

Fixed cost consists of floor space and computer software. Fixed costs are expressed as:

$$-\sum_{n=1}^{N}[(\sum_{a=1}^{A}\epsilon_{a,n}Y_{a,n}) + (\sum_{b=1}^{B}\epsilon_{b,n}Z_{b,n})](1-t)r_n$$

In the above expression $\epsilon_{a,n}$ and $\epsilon_{b,n}$ corresponds to the average estimated fixed cost in period n due to machines a and b respectively. In fact fixed cost can be assigned to operations depending on whether or not they are processed on a given machine. That means parameter $\epsilon_{i,j,.,n}$ can be taken into account instead $\epsilon_{.,n}$. But this requires, for computational purposes to formulate the above expression as:

$$-\sum_{n=1}^{N}[(\sum_{i=1}^{I}\sum_{j=1}^{J_i}\sum_{a=1}^{A}[X_{i,j,a,n}/(X_{i,j,a,n}+\rho)]\epsilon_{i,j,a,n}Y_{a,n})+(\sum_{i=1}^{I}\sum_{j=1}^{J_i}\sum_{b=1}^{B}[X_{i,j,b,n}/(X_{i,j,b,n}+\rho)]\epsilon_{i,j,b,n}Z_{b,n})](1-t)r_n$$

where ρ is a small enough number depending on the precisition of the computer. However the objective function turns out to be nonlinear.

Setup costs are considered next as follows:

$$-\sum_{n=1}^{N}[(\sum_{i=1}^{I}\sum_{j=1}^{J_i}\sum_{a=1}^{A}\alpha_{i,j,a,n}(X_{i,j,a,n}/L_{i,n})) + (\sum_{i=1}^{I}\sum_{j=1}^{J_i}\sum_{b=1}^{B}\alpha_{i,j,b,n}(X_{i,j,b,n}/L_{i,n}))](1-t)r_n$$

As with the capacity constraints this is nonlinear, but can be linearized in a similar manner.

Waiting costs are considered as Park & Son (1988) argue. It is assumed that there is no additional waiting due to early arrival of parts and material handling system carries the parts to the machines lot by lot. Thus the effect of the material handling system results in wating time of a unit at operation $j \in J_i$ at machines $a \in A$ and $b \in B$ respectively as:

$$t_{i,j,a}(L_{i,n} - 1)$$

and

$$t_{i,j,b}(L_{i,n} - 1)$$

If lot size equals one waiting costs disappear. This motivates to invest in machines which allow smaller lot sizes i.e. which have reduced setup costs. Thus waiting costs are written as:

$$-\sum_{n=1}^{N}[(\sum_{i=1}^{I}\sum_{j=1}^{J_i}\sum_{a=1}^{A}\beta_{i,j,n}X_{i,j,a,n}t_{i,j,a}(L_{i,n} - 1)) + (\sum_{i=1}^{I}\sum_{j=1}^{J_i}\sum_{b=1}^{B}\beta_{i,j,n}X_{i,j,b,n}t_{i,j,b}(L_{i,n} - 1))]r_n$$

If the equipment has excess capacity idle time is inevitable. The idle time associated with planned excess capacity need not to be penalized. However if a machine does not have the required operational capability then production can not be assigned to it. This may result in unplanned an idle time. In our model machines which have unplanned excess capacity are penalized by an idle cost as follows:

$$-\sum_{n=1}^{N}[\sum_{a=1}^{A}\gamma_a IT_{a,n} + \sum_{b=1}^{B}\gamma_b IT_{b,n}]r_n$$

The cash outflow due to the installation of new machines is calculated next. The capital cost of new machines may differ form period to period and thus the following term is included:

$$-\sum_{n=1}^{N}\sum_{b=1}^{B}(Z_{b,n} - Z_{b,n-1})F_{b,n}r_n$$

For machine $b \in B$ the term $(Z_{b,n} - Z_{b,n-1})$ equals one only once: at the beginning of the period that b is installed.

Similarly salvage incomes of phased out machines are considered as follows:

$$+\sum_{n=1}^{N}\sum_{a=1}^{A}(Y_{a,n-1} - Y_{a,n})S_{a,n}r_n$$

In the above expression tax is not considered because usually it is negligible.

The depreciation amounts and book value of assets are computed in the constraints and included in the objective function as:

$$+\sum_{n=1}^{N}[\sum_{a=1}^{A} DP_{a,n} + \sum_{b=1}^{B} DP_{b,n}]t\ r_n$$

$$+BV_N r_N$$

5.6 Flexibility Considerations and Postoptimality Analysis

Finally we discuss various types of flexibility considered in the model. Flexibility type definitions assumed here have been explained in Chapter 2. Aggregate flexibilities are not discussed since they are hard to model. However market flexibility can be investigated by different scenarios of market conditions i.e. expected demand. Similarly production flexibility can be investigated by scenario analysis for products that are expected to be introduced. Modeling the transportation between machines as separate operations was not attempted therefore, material handling flexibility is not discussed below. As mentioned above it is assumed that material handling system carries the parts from one machine or FMC to another lot by lot. Furthermore, because a specific set part types is presumed to be given, operation flexibility is not considered explicitly. On the other hand an increase in operation flexibility is indicated by comparing the capability incidence matrices $w_{.,.,a}$ to the capability incidence matrices for the optimal set of modules. Let $o \in O$ denote the optimal set of modules. Then

$$\sum_{j \in J_i} \sum_{o \in O} (w_{i,j,o} - w_{i,j,a})$$

is the increase or decrease in the number of ways that operation $j \in J_i$ can be processed. In brief our replacement model investigates machine flexibility directly and some other flexibility types indirectly.

- **Machine Flexibility:** Machine flexibility is represented by operation capabilities (binary valued parameters $w_{i,j,a}$ and $w_{i,j,b}$). A setup cost associated with utilizing each operation capability is included in the objective function. The mathematical solution procedure will try to avoid assigning operations to a machine if there is a large setup cost. Thus investment in new machines with reduced setup costs is motivated indirectly. Moreover if operations are not assigned to machine because of high setup costs then the idle cost of that machine increases. This tradeoff between setup and idle costs will have an important role in the justification of investment in new machines. At the same time economical production of smaller lot sizes is possible with reduced setup costs. Smaller lot sizes may result in a better NPV because of decreased waiting costs. For smaller lot sizes net savings from waiting costs will have a major role in the justification of the capital expenses of the new machines. Thus the model incorporates a complex set of interrelations to determine the increased machine flexibility gained by implementing the new machines.Increased machine flexibility is indicated by:

$$\sum_{i \in I} \sum_{j \in J} \sum_{o \in O} w_{i,j,o} - \sum_{i \in I} \sum_{j \in J} \sum_{a \in A} w_{i,j,a}$$

  which is the total number of part operations added by the optimal solution.

- **Process Flexibility:** Process flexibility is a result of machine flexibility. Minimizing setup cost and time has a direct impact on this flexibility. Process flexibility is indirectly considered in the above model by motivating reduced setup cost and time. As indicated in table[2.1] one measure for process flexibility is the mix of parts that the system can produce without loosing efficiency. Thus by performing postoptimality analysis on the demand one can determine the range of demands for each product for which demand space remains optimal and gain insight into the range of product mixes the system can produce.

- **Product Flexibility:** Since a set of part types to be produced is assumed given, only the changes in production mix of the given part types can be considered. Thus the ease of change with which the part mix currently being produced is increased by motivating reduced setup costs and time and smaller lot sizes. Since the solution is determined by demand one can find the demand space over which the replacement sequence remains optimal to understand indirectly product flexibility obtained.

- **Routing Flexibility:** Alternate rountings are made possible by the redundancy in operation capabilities as well as versatility of the machines. At the end of the planning horizon redundancy is made sure for operation capabilities required by more than one part type. The set redundancy constraints could significantly lower the optimal NPV. The model should be solved with and without these constraints in order to see the difference between optimal NPV values indicating the cost of having redundant operation capabilities. At the same time, because additional loads are imposed on alternate machines (in case of machine breakdowns for example) a capacity slack factor φ is introduced to attain routing flexibility.

- **Expansion Flexibility:** For the our problem of incremental implementation of flexible automation expansion flexibility is assumed to exist. That is an incremental implementation is considered as the utilization of expansion flexibility over the planning horizon. Additional expansion flexibility will depend on the design of the individual modules in the optimal solution.

- **Volume Flexibility:** Given the capacity constraints volume flexibility can be investigated by the resulting NPV for different scenarios of demand. However idle cost in the objective function may need not to be considered.

5.7 Binary versus Integer Variables

In our model formulation one module consists of one machine. In his similar multimachine replacement model Suresh (1989) assumes that one module consists of more than one machines of the same type. However in a typical manufacturing system each machine has usually at least one different characteristic than the others. Cost items associated with machines may be different or idle time may be desirable for one machine while is not desirable for other machines. Because Suresh assumes more than one machine in a module, he introduces decision variables associated with number of machines that are operating in a given period as integer variables. Thus production assignments are made to the modules. How to divide a production assignment of a module between the machines yields to another problem. Therefore we assume one machine for each module and introduce a binary variable associated with each module that are operating in a given period. This allows one to consider idle time of each machine individually and the solution results in a detailed production plan. However the number of binary and continuous variables increases proportional to number of machines. A mixed integer formulation is also possible by rearranging the input data and foregoing a detailed production plan.

Chapter 6

Conclusions and Future Research

A large literature pertaining to flexibility has accumulated over the last decade. However there exist differences of opinion on various ways of to formalize flexibility concept. ' Literature makes one thing abundantly clear: flexibility is multidimensional and complex ' [Sethi & Sethi (1990) p:289].

Understanding flexibility is made difficult by its multidimensional nature. Based on a detailed review of the literature we have classified the conceptual frameworks on formalizing flexibility as

- type based understanding,
- change based understanding.

Both type based and change based approaches contribute a great deal to understanding the multidimensional nature of flexibility. Literature mainly focuses on the type based understanding and thus flexibility types have become a communication tool. On the other hand, some authors [Kumar (1986), Gupta & Buzacott (1988), Sethi & Sethi (1990), Chung & Chen (1989)] agree that flexibility types cause a confusion. We suggested the change based approach can provide a greater understanding of flexibility to managers whose knowledge about technological details is limited. Thus we have expanded Suresh's

(1990.b) capability-ease definition to provide a basis for the understanding and shown that it is equivalent to Buzacott and Gupta's (1988) sensitivity and stability concepts for change based understanding of flexibility.

There have been a prevailing discussion between researchers on how flexibility relates to system performance. In fact, type based and change based approaches are two different ways of determining relevant performance measures associated with flexibility. Most experts argue that performance evaluation of flexible systems needs to be carried out by a task force which consists of system engineers and managers. This is due to the fact that continuous performance improvement can be achieved throughout organizational learning and experimentation, and active management participation. Thus we have suggested a framework, ' capability - ease approach ', for the analysis of relevant performance measures. If it is followed by a task force, capability - ease approach can contribute to a greater understanding of flexibility which lead to the selection of more appropriate performance measures.

We have developed a mixed-zero-one, nonlinear programming, multimachine, multiperiod, replacement model for incremental implementation of flexible automation. Capability and ease notions are adapted for modeling flexibility and a reclassification of costs has been considered. A reclassification of costs is included in order to assess all true costs and benefits of flexible technology. Opportunity costs of not having flexibility are taken into account in order to investigate the foregone benefits by retaining the existing technology. Thus some specific aspects of designing flexibility and less obvious benefits of this technology have been modeled in contrast to machine-level equipment replacement problem. Modeling the impact of material handling system have not been attempted, rather remained as an area of future research.

Since the model is aimed at meeting a given demand , there is no additional opportunity costs due to lost profit of making more products during idle and waiting times. Thus waiting cost per each operation is considered to be the cost of tied up capital in raw material for our input data.

During the planning horizon material costs can change, and thus waiting cost/time $\beta_{i,j,n}$ of unit operation (i,j) in period n is computed as:

$$\beta_{i,j,n} = \frac{C_{i,n} \quad k}{\text{number of hours in a year (8766)}}$$

In a similar manner, idle cost is considered to be tied up capital to the machines. For current machines $a \in A$ idle cost/time γ_a is computed as:

$$\gamma_a = \frac{F_a \quad CRF}{K_a}$$

where CRF is the capital recovery factor. However for new machines $b \in B$ idle cost/time γ_b is computed as

$$\begin{aligned} \gamma_b &= \frac{F_b \quad CRF}{K_b} \\ F_b &= F_{b,n} \quad \text{where} \quad Z_{b,n} - Z_{b,n-1} = 1. \end{aligned}$$

That is F_b depends on the period that b is installed. Thus γ_b is formulated as:

$$\gamma_b = \sum_{n=1}^{N} (Z_{b,n} - Z_{b,n-1}) F_{b,n} \frac{CRF}{K_b}$$

This γ_b factor adds nonlinearity to the objective function.

Obtaining efficient solution procedures and computational results are our future research areas. The binary decision variables of the nonlinear model can be converted into general integer variables in order to decrease the number of binary and continuous decision variables as discussed at the end of Chapter 5. In order to avoid nonlinearity in the objective function additional nonlinear constraints can be formulated and Lagrangian multipliers can be used to keep the constraint set linear. It may be possible to gain computational efficiency by developing branch and bound algorithm which branches on the 0-1 variables. Thus the model may be linearized for each branch and bound iteration.

Bibliography

A. Arbel and A. Seidman. Performance evaluation of flexible manufacturing systems. *IEEE Trans. on Systems, Man and Cybernetics*, 14:606–617, 1984.

G. Azzone and U. Bertele. Measuring the economic effectiveness of flexible automation: A new approach. 27:735–746, 1989.

R.A. Berdine. Caterpillar's dnc systems 2.5 years later. In *Proc. of 15th Conference on Numerical Control*, page 110, 1978.

J. Bessant and B. Haywood. Flexibility in manufacturing systems. 14:465–473, 1986.

C.R. Boer and V. Meltzer. Economic evaluation of advanced manufacturing by means of simulation. *Materiel Flow*, 3:215–224, 1986.

H. Boer, M. Hill, and K. Krabbendam. Fms implementation management: Promise and performance. *International Journal of Operations and Production Management*, 10:5–20, 1990.

P.H. Brill and M. Mandelbaum. On measures of flexibility in manufacturing systems. 27:747–756, 1989.

J. Browne et al. Classification of flexible manufacturing systems. *The FMS Magazine*, April:114–117, 1984.

M. C. Burstein. Finding the economical mix of rigid and flexible automation for manufacturing systems. In K. E. Stecke and R. Suri, editors, *Second ORSA/TIMS Conference on Flexible Manufacturing Systems*, pages 43–54. Elsevier, 1986.

M. C. Burstein and M. Talbi. Economic evaluation for the optimal introduction of flexible manufacturing technology under rivalry. In K. E. Stecke and R. Suri, editors, *Annals of Operations Research Vol. 3*, pages 81–112. J. C. Baltzer AG, 1985.

M.C. Burstein. Rigid and flexible automation for manufacturing systems: Characterizing economically reasonable inv. *Annals of Operations Research*, 15:21–35, 1988.

J. Buzacott. The fundamentel principles of flexibility in manufacturing systems. In *Flexible Manuf. Systems, Proc. of the First Int. Conf. (Brighton, UK)*, pages 13–22. Elsevier, 1982.

J. Buzacott and D. Gupta. Impact of flexible machines on automated manufacturing systems. In Stecke K.E. and R.Suri, editors, *Proc. of the Second ORSA/TIMS Conf. on Flexible Manuf. Systems*, pages 257–268. Elsevier, 1986.

J. A. Buzacott and D. D. Yao. Flexible manufacturing systems: A review of analytical models. 32:890–905, 1986.

J.A. Buzacott and J.G. Shanthikumar. Models for understanding flexible manufacturing systems. *AIIE Transactions*, 12:339–350, 1980.

M.F. Carter. Designing flexibility into automated manufacturing systems. In K.E. Stecke and R. Suri, editors, *Second ORSA/TIMS conf. on Flexible Manufacturing Systems*, pages 107–118. Elsevier, 1986.

J.P. Caulkins and C.H. Fine. Seasonal inventories and the use of product-flexible manufacturing technology. Technical report, MIT Operations Research Center, 1990.

A. Chatterjee, M. Cohen, et al. Manufacturing flexibility: Models and measurement. In *First ORSA/TIMS special interest cof. on FMS*, pages 49–64. Ann Arbor, MI, 1984.

A. Chatterjee et al. Manufacturing flexibility: Models and measurements. In *Proc. of the First ORSA/TIMS Conf. on FMS*, pages 49–64, 1984.

F. Choobineh. Justification of flexible manufacturing systems. In F. Choobineh and R. Suri, editors, *FMS Current Issues*, pages 269–281. IIE Press, 1986.

F. Choobineh and R. Suri, editors. *Evaluating the "Intangible" Benefits of Flex. Manuf. Systems by Use of DCF Algorithms.* IIE, 1986a.

C.H. Chung and I.J. Chen. A systematic assessment of the value of flexibility for an fms. In Stecke K.E. and R. Suri, editors, *Proc. of the Third ORSA/TIMS Conference on Flexible Manuf. Systems*, pages 27–32. Elsevier, 1989.

T. Cox. Toward the measurement of manufacturing flexibility. *Production and Inventory Management Journal*, 1Quart:68–72, 1989.

G.S. Day and L. Fahey. Putting strategy into shareholder value analysis. *Harward Business Review*, pages 156–162, 1990.

C. Dupont-Gatelmand. Key success factors for fms design and implementation. In K. Rathmill, editor, *2nd. International conf. on Flexible Manufacturing Systems*, pages 282–293. IFS, 1983.

J.E. Ettlie. Implementation strategies for discrete part manufacturing technologies. Technical report, Univ. of Michigan, 1988.

C.H. Falkner. Flexibility in manufacturing plants. In K.E. Stecke and R. Suri, editors, *Second ORSA/TIMS conf. on Flexible Manufacturing Systems*, pages 95–106. Elsevier, 1986.

C.H. Falkner. Multi-attribute decision analysis for justifying flexibile automation. In *Proc. of IEEE International Confrence on Robotics and Automation*, pages 1815–20, 1986b.

C.H. Falkner and S.Benhajla. Multi-attribute decision models in the justification of cim systems. *The Engineering Economist*, 35:91–114, 1990.

C. H. Fine. Developments in manufacturing technology and economic evaluation models. In S. C. Graves et al., editors, *Logistics of Production and Inventory (to appear)*. North Holland Series in OR, 1989.

C.H. Fine. Economic analysis of product-flexible manufacturing system investment decisions. In Stecke K.E. and R. Suri, editors, *Proc. of the Second ORSA/TIMS Conf. on Flexible Manuf. Systems*, pages 55–68. Elsevier, 1986.

C.H. Fine and R.M. Freund. Optimal investment in product-flexible manufacturing capacity. 36:449–466, 1990.

C.H. Fine and A.C. Hax. Manufacturing strategy: A methodology and an illustration. *Interfaces*, 15:28–46, 1985.

C.H. Fine and L. Li. Technology choice, product life cycles and flexible automation. *Journal of Manufacturing and Operations Management*, 1:372–399, 1988.

R.M. Freund and C.H. Fine. Optimal investment in product-flexible manufacturing capacity, part2: Computing solutions. Technical report, MIT Sloan School of Management, 1986.

C. Gaimon. The strategic decision to acquire flexible technology. In Stecke K.E. and R. Suri, editors, *Proc. of the Second ORSA/TIMS Conf. on Flexible Manuf. Systems*, pages 69–81. Elsevier, 1986.

D. Gerwin. A theory of innovation processes for computer-aided manufacturing technology. *IEEE Transactions on Engineering Management*, 35:90–100, 1988.

J. D. Goldhar and M. Jelinek. Computer integrated flexible manufacturing: Organizational, economic and strategic implications. Technical report, 1985.

J. D. Goldhar and M. Jelinek. Plan for economies of scope. *Harvard Business Review*, Nov-Dc:141–148, 2983.

D. Gupta and J. A. Buzacott. Multiproduct industries: A case for flexible automation. In K. E. Stecke and R. Suri, editors, *Third ORSA/TIMS Conference on Flexible Manufacturing Systems*, pages 35–40. Elsevier, 1989.

D. Gupta and J.A. Buzacott. A framework for understanding flexibility of manufacturing systems. Technical report, Univ. of Waterloo, 1988.

D. Gupta et al. Economic analysis of investment decisions in flexible manufacturing systems. Technical report, University of Waterloo, 1988.

D. Gupta et al. The optimal mix of flexible and dedicated manuf. capacities: Hedging against demand uncertainty. Technical report, McMaster University, 1990.

D. Gupta and J.A.Buzacott. Notions of flexibility in manufacturing plants. Technical report, Univ. of Waterloo, 1986.

M. Hammer. Reengineering work: Don't automate, obliterate. *Harvard Business Review*, Jul-Au:100–112, 1990.

J. Harter and C.J. Mueller. Fms at remington. *Manufacturing Review*, Mar:91–95, 1988.

P. Y. Haung and C. S. Chen. Flexible manufacturing systems: An overview and bibliography. *Production and Inventory Management*, 3. qua:80–90, 1986.

M.J. Henneke and R.H. Choi. Evaluation of fms parameters on overall system performance. *Computers and Industrial Engineering*, 18:105–110, 1990.

J.E. Hodder. Evaluation of manufacturing investments: A comparison of u.s. and japanese investments. *Financial Management*, Spring:17–24, 1986.

P.G. Hough. Cost estimating for the factory of the future. In Stecke K.E. and R. Suri, editors, *Proc. of the Third ORSA/TIMS Conf. on Flexible Manuf. Systems*, pages 53–58. Elsevier, 1989.

G. K. Hutchinson and J. R. Holland. The economic value of flexible automation. *Journal of Manufacturing Systems*, 1:215–228, 1982.

Y. Ito. Evaluation of fms: The state of the art regarding how to evaluate system flexibility. *Robotics and Computer Integrated Manuf.*, page 3, 1987.

R. Jaikumar. Postindustrial manufacturing. *Harvard Business Review*, Nov-de:69–76, 1986.

J.K. Kaeli. A company-wide perspective to identify, evaluate and rank the potential for cim. Jul:23–27, 1990.

R. S. Kaplan. Must cim be justified by faith alone. *Harvard Business Review*, Ma-Apr:239–247, 1986.

A. Kiran and B.C. Tansel. The system setup in fms. In Stecke K.E. and R. Suri, editors, *Proc. of the Second ORSA/TIMS Conf. on Flexible Manuf. Systems*, pages 321–332. Elsevier, 1986.

H.T. Klahorst. How to justify multimachine systems. *American Machinist*, Sep:67–70, 1983.

N. Kulatilaka. Financial, economic and strategic issues concerning the decision to invest in advanced automation. 22:949–968, 1984.

N. Kulatilaka. Capital budgeting and optimal timing of investments in flexible manufacturing systems. In K. E. Stecke and R. Suri, editors, *Annals of Operations Research Vol. 3*, pages 35–58. J. C. Baltzer AG, 1985.

N. Kulatilaka. Valuing the flexibility of flexible manufacturing systems. *IEEE Transactions on Eng. Mgmt.*, 35:250–257, 1988.

N. Kulatilaka and S.G. Marks. The strategic value of flexibility: Reducing the ability of compromise. *The American Economic Review*, 78:574–580, 1988.

V. Kumar. On measurement of flexibility in flexible manufacturing systems: An information theoritic approach. In Stecke K.E. and R.Suri, editors, *Proc. of the Second ORSA/TIMS Conf. on Flexible Manuf. Systems*, pages 137–143. Elsevier, 1986.

A. Kusiak, editor. *Flexible Manufacturing Systems: A Review of Modelling Approaches for Design, Justification and Oper.* Elsevier, 1986.

A. Kusiak, editor. *Modelling a System of Flexible Manufacturing Cells.* Elsevier, 1986.

A. Kusiak, editor. *Multiobjective Decision Making for a Flexible Manufacturing System.* Elsevier, 1986.

M. Kuula and A. Stam. A nonlinear multi-criteria model for strategic fms selection decisions. Technical report, IIASA, 1989.

D. Littler and R.C. Sweeting. The management of new technology based business: The existentialist firm. 18:231–240, 1990.

M. Mandelbaum and J.A. Buzacott. Flexibility and its use:a formal decision process and manufacturing view. In Stecke K.E. and R. Suri, editors, *Proc. of the Second*

ORSA/TIMS Conf. on Flexible Manufacturing Systems, pages 118–130. Elsevier, 1986.

M. Mandelbaum and Buzacott J. Flexibility and decision making. 44:17–27, 1990.

J.R. Meredith, editor. *Conditions Under which Flexible Manufacturing is Financially Viable.* IIE, 1986b.

J.R. Meredith and N.C. Suresh. Justification techniques for advanced manufacturing technologies. *International Journal of Production Research*, 24:1043–1057, 1986.

P.E. Moody, editor. *New Manufacturing Technologies.* Dow-Jones Irwin, 1990.

C. A. Nelson. A mathematical programming formulation of elements of manufacturing strategy: Fms applications. In K. E. Stecke and R. Suri, editors, *Second ORSA/TIMS Conference on Flexible Manufacturing Systems*, pages 31–42. Elsevier, 1986.

J.V. Owen. Flexible justification for flexible cells. *Manufacturing Engineering*, Sep:39–45, 1990.

C.S. Park and Y.K. Son. An economic evaluation model for advanced manufacturing systems. *The Engineering Economist*, 34:1–26, 1988.

H.R. Parsaei et al., editors. *Decision Support for Value Analysis of Integrated Manufacturing Technology.* Elsevier, 1990.

H.R. Parsaei and Wilhelm M.R. A justification methodology for automated manufacturing technologies. *Computers and Industrial Engineering*, 16:363–373, 1989.

P.L. Pollard and R.L. Tapscott. Investment evaluation methodology. In Stecke K.E. and R. Suri, editors, *Proc. of the Third ORSA/TIMS Conf. on Flexible Manuf. Systems*, pages 47–52. Elsevier, 1989.

P.L. Primrose and R. Leonard. The development and application of a computer based appraisal technique for the structured evaluat. *Proc. of I.Mech.E.*, 198:142–146, 1984.

P.L. Primrose and R. Leonard. The use of a conceptual model to evaluate financially flexible manufacturing system projects. *Proc. of I.Mech.E.*, 199:15–21, 1985.

P.L. Primrose and R. Leonard. Identifying the flexibility of fms systems. In *Proc. of 26th Machine Tool Design and Research Conf.*, pages 167–173, 1986.

P.L. Primrose and R. Leonard. The financial evaluation and economic application of advanced manufacturing technology. *Proc. of the I.Mech.E.*, 200:27–31, 1986c.

T.W. Schlie and J.D. Goldhar. Product variety and time based manuf. and business management: Achieving competitive advantage. *Manufacturing Review*, 2:32–42, 1989.

A. K. Sethi and S. P. Sethi. Flexibility in manufacturing: A survey. *The International Journal of Flexible Manufacturing Systems*, 2:289–328, 1990.

K. Singhal, C. H. Fine, et al. Research and models for automated manufacturing. *Interfaces*, 17 : 6:5–14, 1987.

H. Sirkin and G. Stalk. Fix the process, not the problem. *Harvard Business Review*, Jul-Au:26–33, 1990.

M.L. Smith et al. Characteristics of u.s. flexible manufacturing systems: A survey. In Stecke K.E. and R. Suri, editors, *Proc. of the Second ORSA/TIMS Conf. on Flexible Manufacturing Systems*, pages 477–486. Elsevier, 1986.

K.S. Son. A cost estimation model for advanced manufacturing systems. 29-3:441–52, 1991.

Y.K. Son and C.S.Park. Economic measure of productivity, quality and flexibility in advanced manufacturing systems. *Journal of Manufacturing Systems*, 6:193–207, 1987.

Y.K. Son and C.S. Park. Quantifying opportunity costs associated with adding manufacturing flexibility. 28:1183–1194, 1990.

V. Srinivasan and R.A. Millen. Evaluating flexible manufacturing systems as a strategic investment. In Stecke K.E. and R.Suri, editors, *Proc. of The Second ORSA/TIMS Conf. on Flexible Manuf. Systems*, pages 83–93. Elsevier, 1986.

A. Stam and M. Kuula. Selecting a flexible manufacturing system using multiple criteria analysis. Technical report, IIASA, 1989.

N. Suresh. An extended multi objective replacement model for flexible automation investments. Technical report, State Univ. of New York, 1990c.

N. Suresh. Flexible automation investments: A sysnthesis of two modellling approaches. Technical report, State Univ. of New York, 1990d.

N. C. Suresh. A muti-objective multi-period replacement model for flexible automation systems. Technical report, State U. of NY at Buffalo, 1990b.

N. C. Suresh and J. Sarkis. A mip formulation for the phased implementation of fms modules. In K. E. Stecke and R. Suri, editors, *Third ORSA/TIMS Conference on Flexible Manufacturing Systems*, pages 41–46. Elsevier, 1989.

N.C. Suresh. A generalized multimachine replacement model for flexible automation investments. Technical report, State University of Newyork, 1989.

N.C. Suresh. Towards an integrated evaluation of flexible automation investments. 28:1657–1672, 1990a.

R. Suri and C.K. Whitney. Decision support requirements in flexible manufacturing. *Journal of Manufacturing Systems*, 3, 1984.

A. J. Triantis and J. E. Hodder. Valuing flexibility as a complex option. *The Journal of Finance*, 45:549–565, 1990.

J.W. Troxler and L.T. Blank. Value analysis for manufacturing technology investments. In *IIE Integrated Systems Conf. Proc.*, pages 24–29, 1987.

M.S. Varney et al. Justification of flexible manufacturing systems with the analytical hierarchy process. In *Annual International Indust. Eng. Conf. Proc.*, pages 181–90, 1985.

U. Wemmerlov and N.L. Hyer. Celluar manufacturing practices. *Manufacturing Engineering*, Mar:79–82, 1989.